

Higgs Physics for Future Colliders

LoopFest XXIV

May 29, 2026

Matthew Forsslund



PRINCETON CENTER FOR
THEORETICAL SCIENCE

The future collider landscape

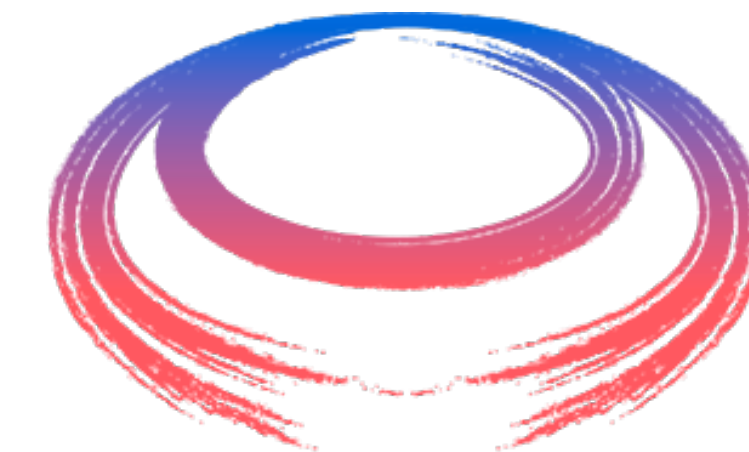


• Future colliders can mean many things:

- HL-LHC
- EIC
- LHeC
- Circular ee : LEP3, FCC- ee
- Linear ee (LCF, CLIC, ...)
- FCC-hh
- Muon Collider (125 GeV, 3/10 TeV, ...)
- Wakefield ee
- Most of these could be considered 'Higgs factories'



Linear Collider Vision

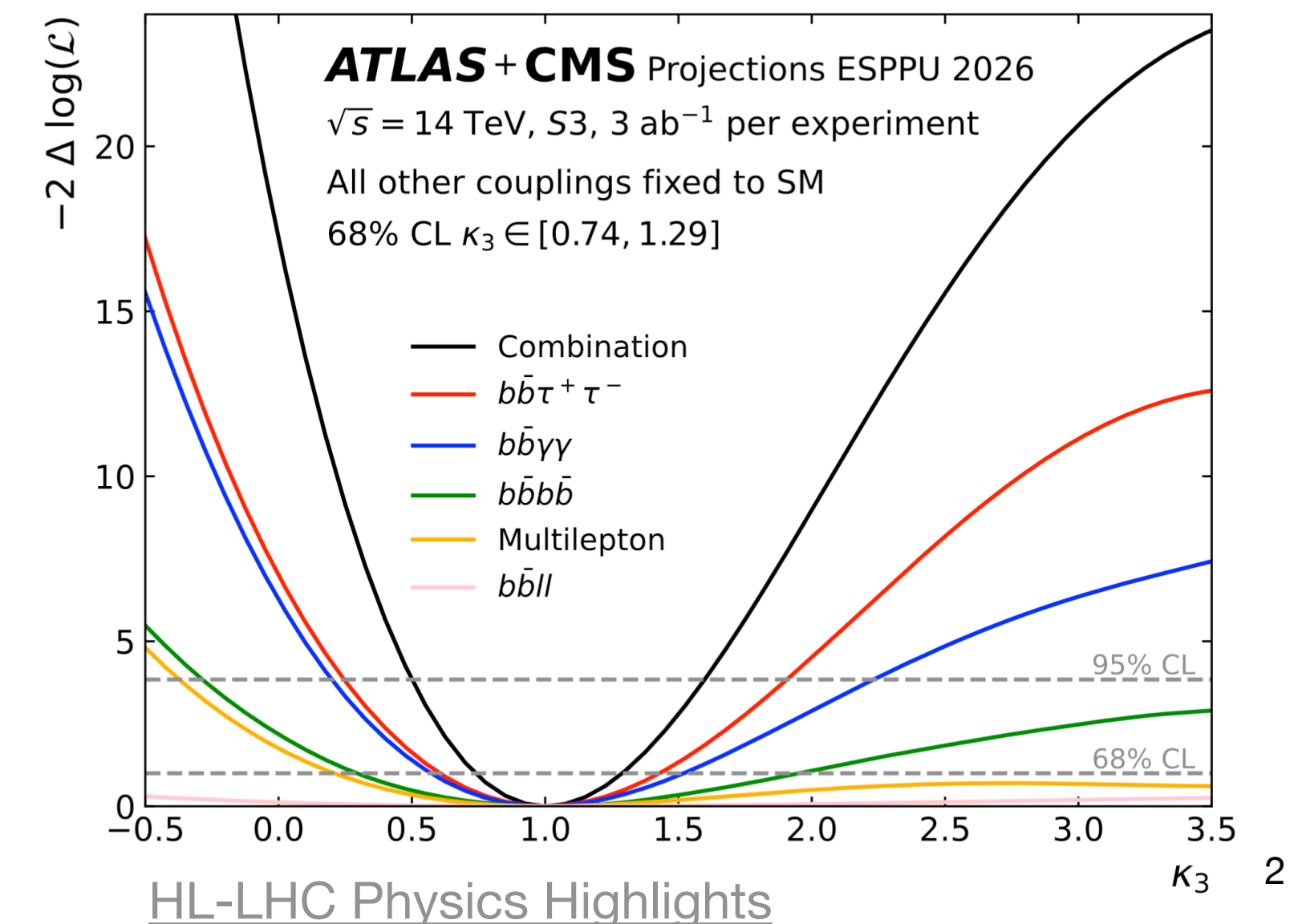
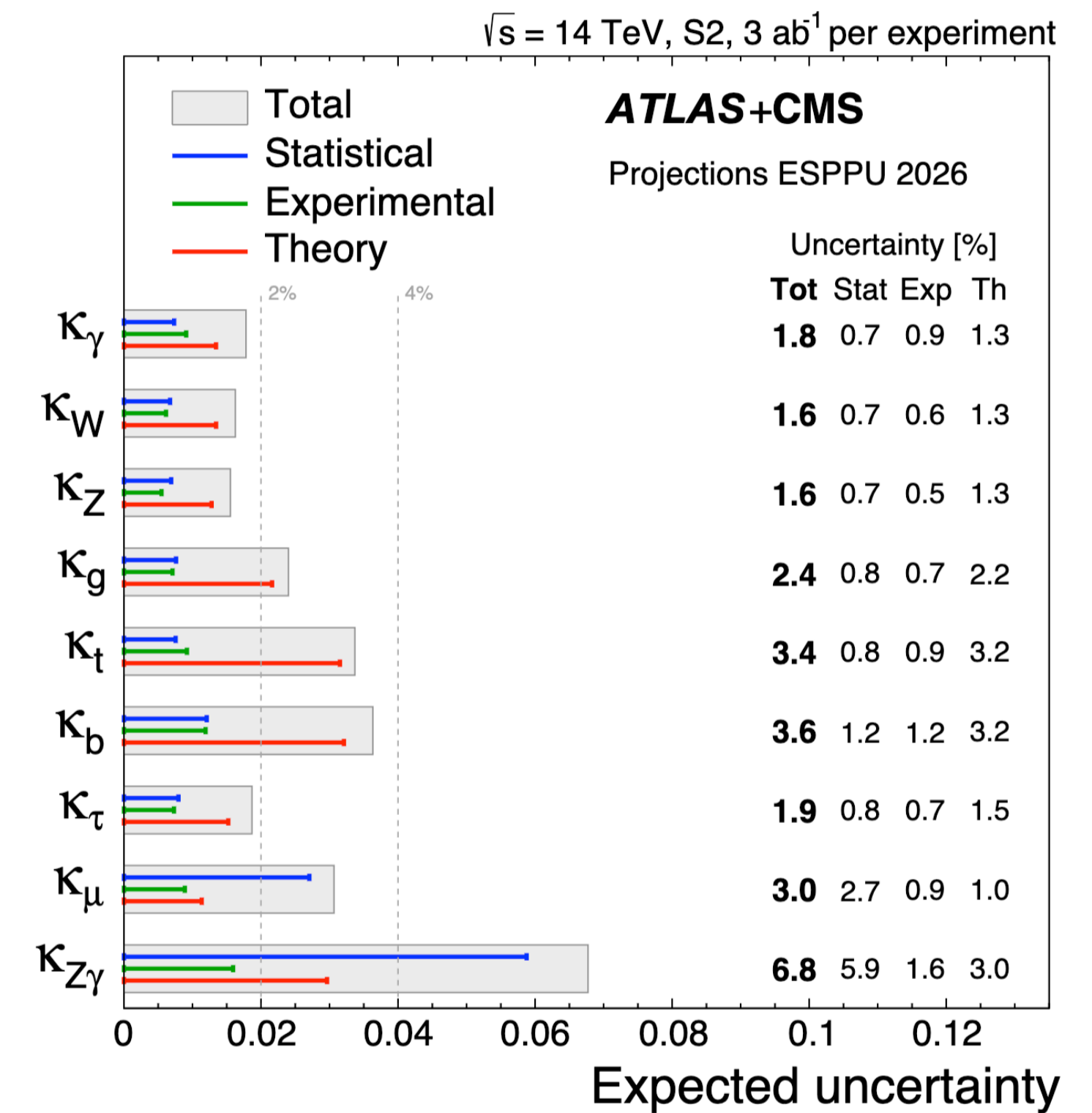


International
Muon Collider
Collaboration



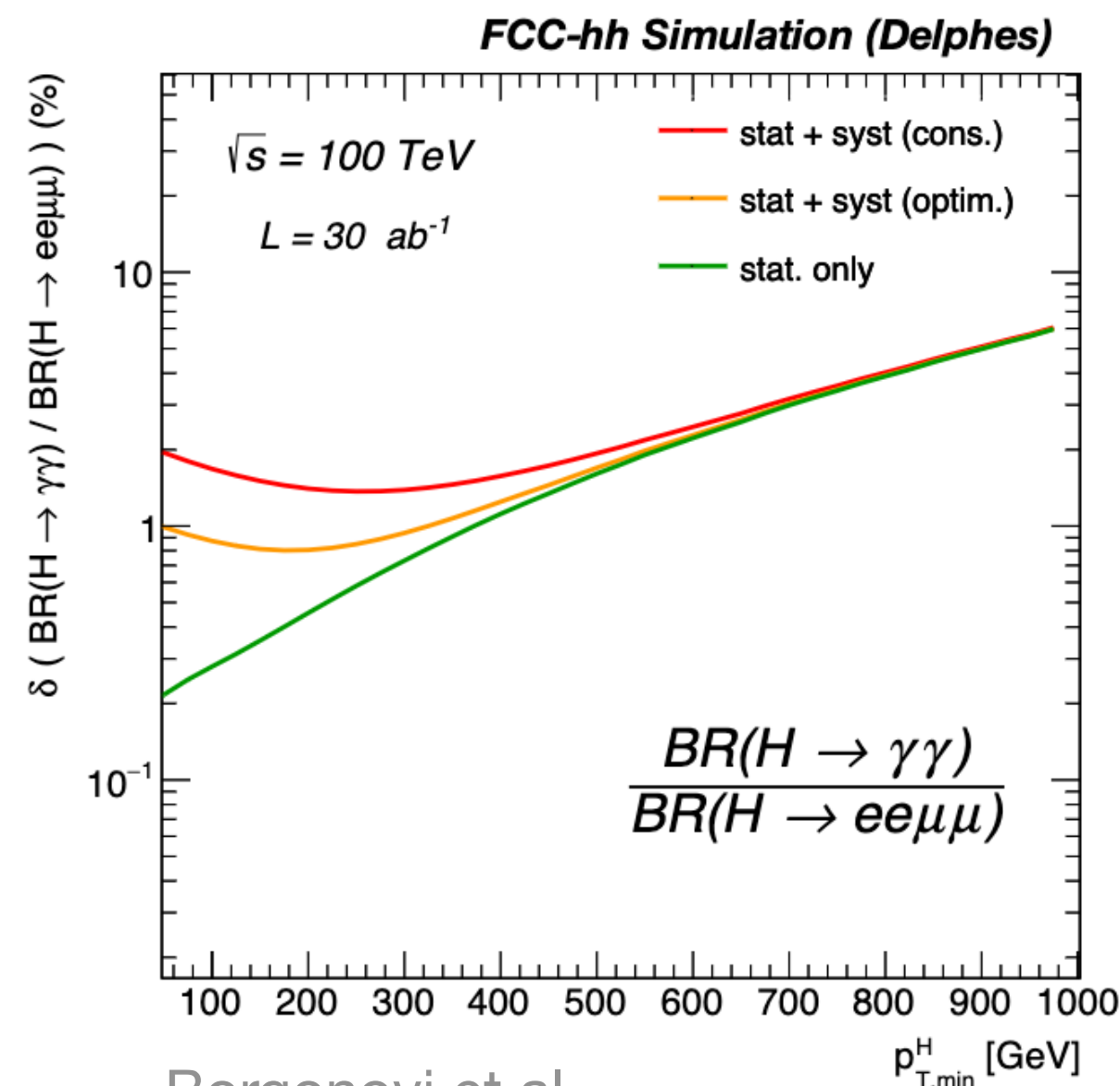
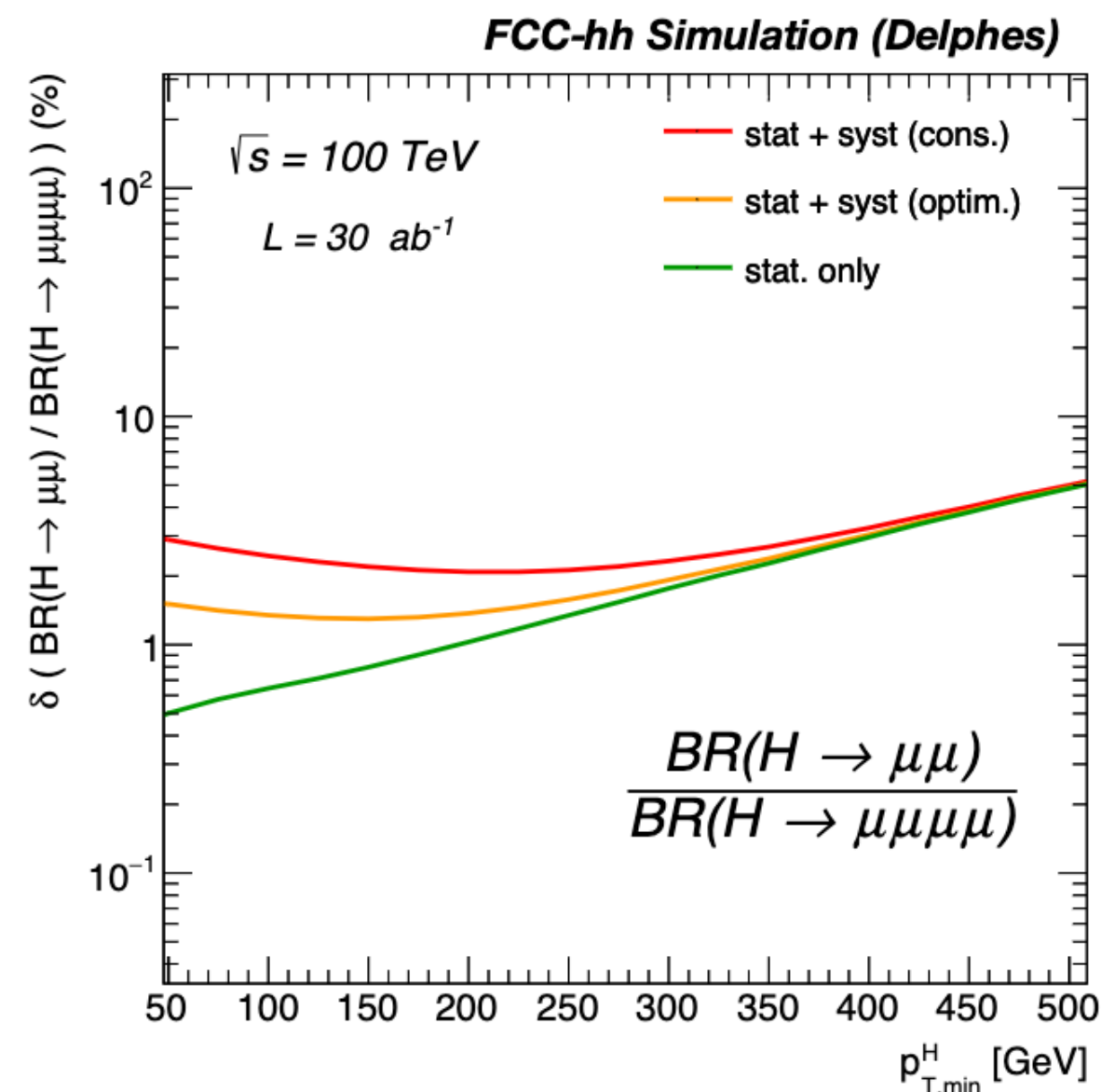
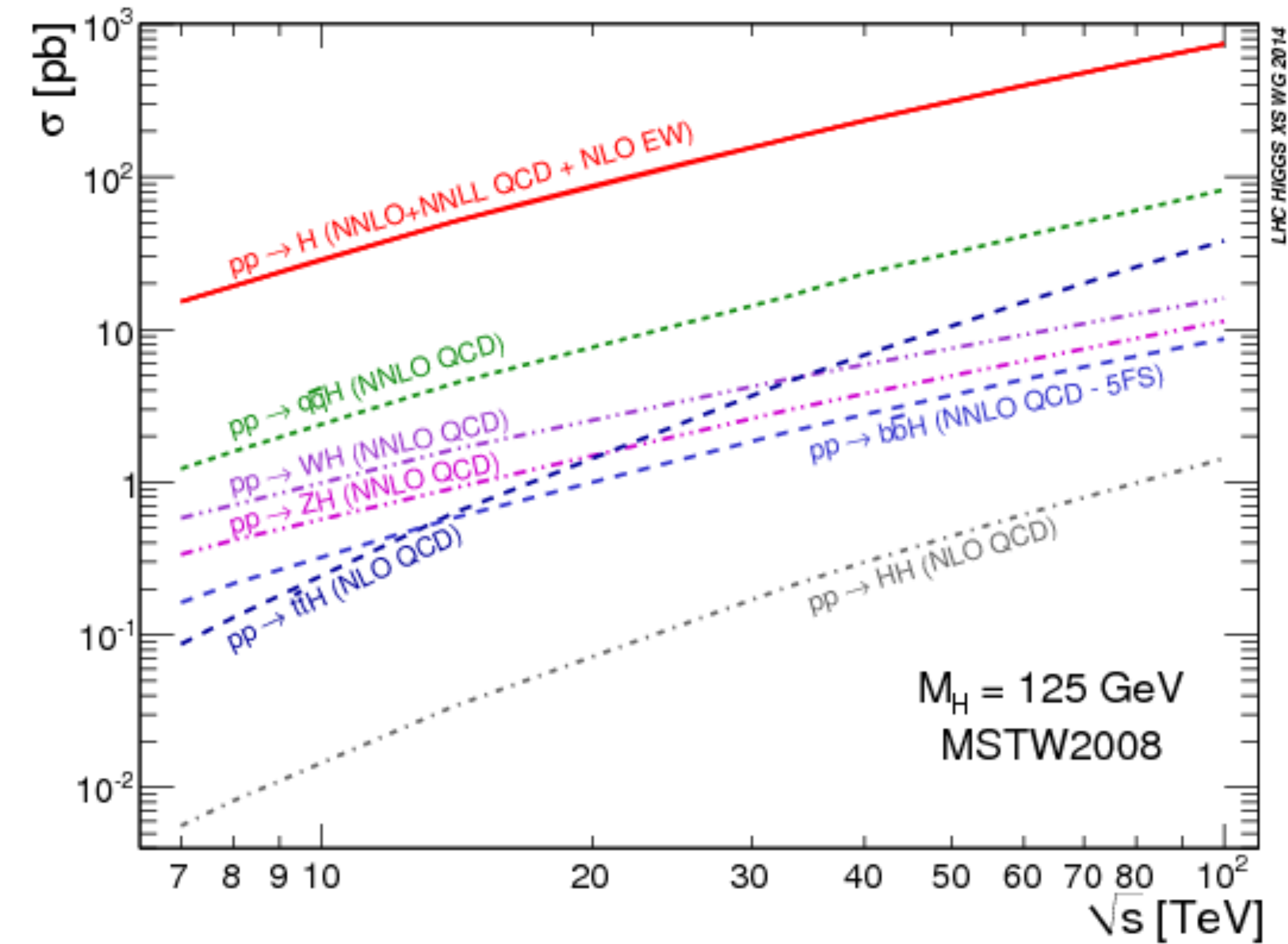
LHC

- LHC is already a Higgs factory: $\mathcal{O}(10^8)$ Higgs by end of HL-LHC
- The challenge is the backgrounds
- Measurements of rare, clean decays ($4\ell, \gamma\gamma, Z\gamma, \mu\mu, \dots$) will not improve much until an eventual FCC-hh
- Other measurements will be largely theory limited (assumes factor of 2 improvement from today)



FCC-hh

- Cross sections $\sim 20\times$ larger at 100 TeV
- With $\sim 20/\text{ab}$ luminosity, $\mathcal{O}(10^{10})$ Higgs
- Biggest qualitative differences from LHC are boosted topologies



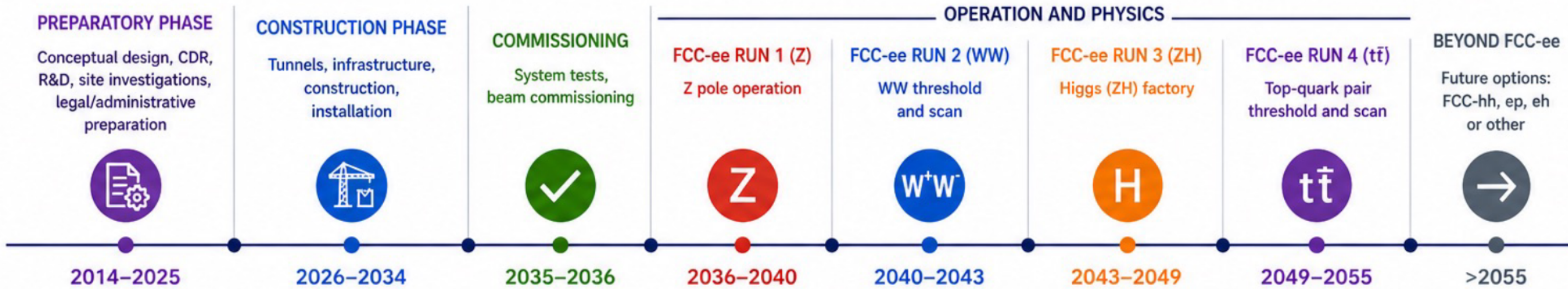
Borgonovi et al

- Obtain high precision on ratios to minimize systematics
- Enough statistics to select only well understood phase space regions

e^+e^- Colliders

Future Circular Collider – e^+e^- (FCC-ee)

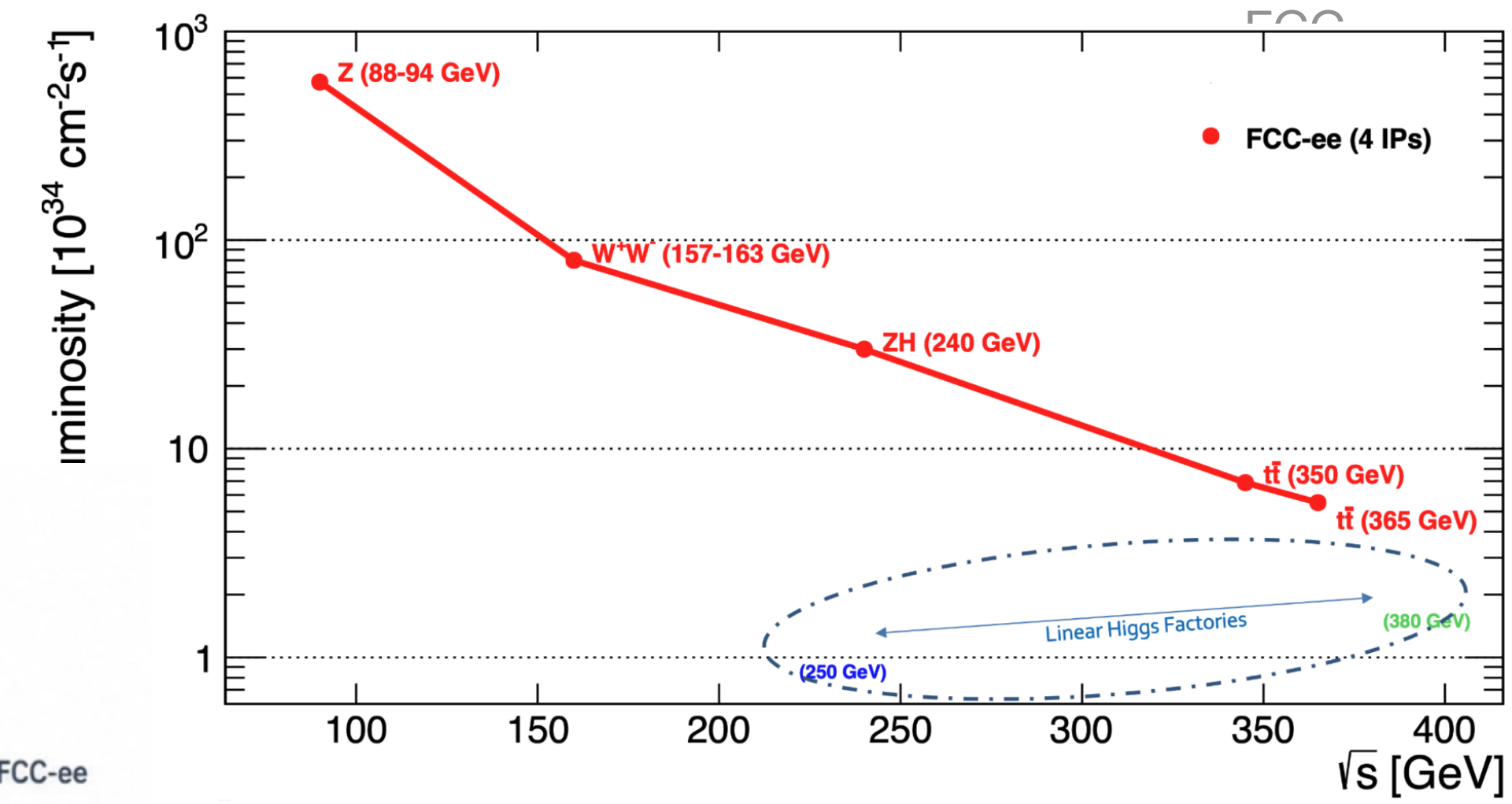
Timeline and Physics Milestones



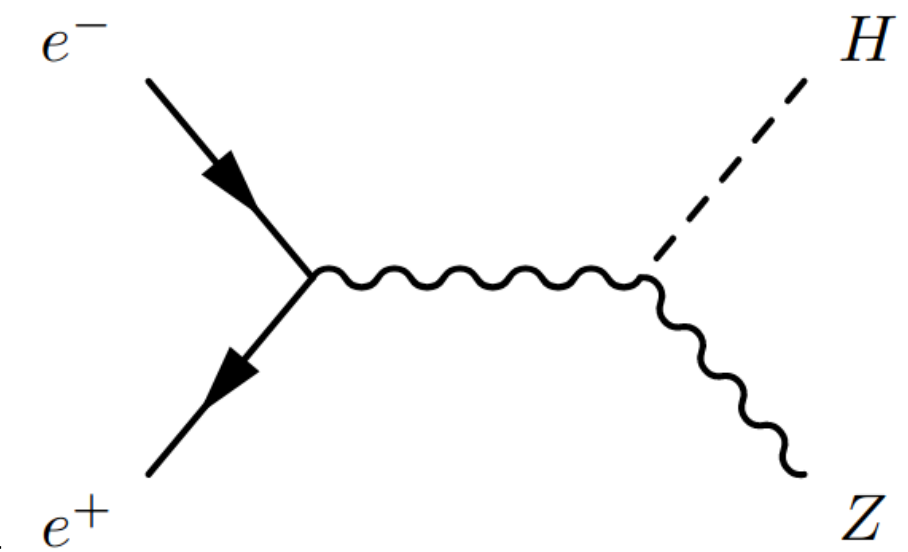
PHYSICS MILESTONES

<p>Z POLE PHYSICS</p> <ul style="list-style-type: none"> 10^{12}–10^{13} Z bosons Precision electroweak measurements Determination of: <ul style="list-style-type: none"> $m_Z, \Gamma_Z, \sin^2\theta_W$ (eff) Number of light neutrinos $\alpha_s(m_Z)$ Rare Z decays Flavour physics with unprecedented precision 	<p>WW THRESHOLD AND SCAN</p> <ul style="list-style-type: none"> $\sim 10^8$ WW pairs Precision of m_W to ~ 500 keV α_{WW} (triple gauge coupling) measurements Search for anomalous gauge couplings QCD studies and tests 	<p>HIGGS FACTORY (ZH)</p> <ul style="list-style-type: none"> ~ 2–5 ab^{-1} at $\sqrt{s} \approx 240$ GeV $\sim 10^6$ Higgs bosons Model-independent Higgs coupling measurements ($\leq 1\%$ level) Higgs width (model-independent) Invisible/rare Higgs decays Higgs self-coupling (indirectly) Searches for exotic decays 	<p>TOP THRESHOLD AND SCAN</p> <ul style="list-style-type: none"> $\sim 10^6$ $t\bar{t}$ pairs Precision of m_{top} to ~ 10 MeV Top Yukawa coupling Top electroweak couplings Top anomalous couplings New physics in top sector 	<p>FUTURE PHYSICS POSSIBILITIES</p> <ul style="list-style-type: none"> Higher energies (FCC-hh) ep / eh collisions Precision QCD & EW BSM searches Complementarity with other facilities
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ENERGY (\sqrt{s})	≈ 90 – 94 GeV	≈ 157 – 163 GeV	≈ 240 GeV	≈ 340 – 365 GeV	≥ 350 GeV and beyond
INTEGRATED LUMINOSITY	≈ 150 ab^{-1}	≈ 10 ab^{-1}	≈ 2 – 5 ab^{-1}	≈ 1.5 ab^{-1}	–
MAIN DELIVERABLES	Ultimate Z physics Electroweak precision QCD & flavour	m_W to ~ 500 keV α_{WW} and EW studies	Precision Higgs physics Couplings at $\leq 1\%$ level	m_{top} to ~ 10 MeV Top physics programme	Exploration at higher energies & new frontiers



e^+e^- Colliders for Higgs physics



- Higgs precision overwhelmingly from Higgstrahlung: $e^+e^- \rightarrow ZH$
- $\mathcal{O}(10^6)$ Higgs produced -- most measurements will be statistics limited
- Theory uncertainty requirements much less strict than at Tera-Z. Relevant wishlist from ESPP:

$H \rightarrow b\bar{b}$ width

$N^4\text{LO}$ ($m_b \neq 0$); $N^4\text{LO}$ differential ($m_b = 0$)

$H \rightarrow gg$ width

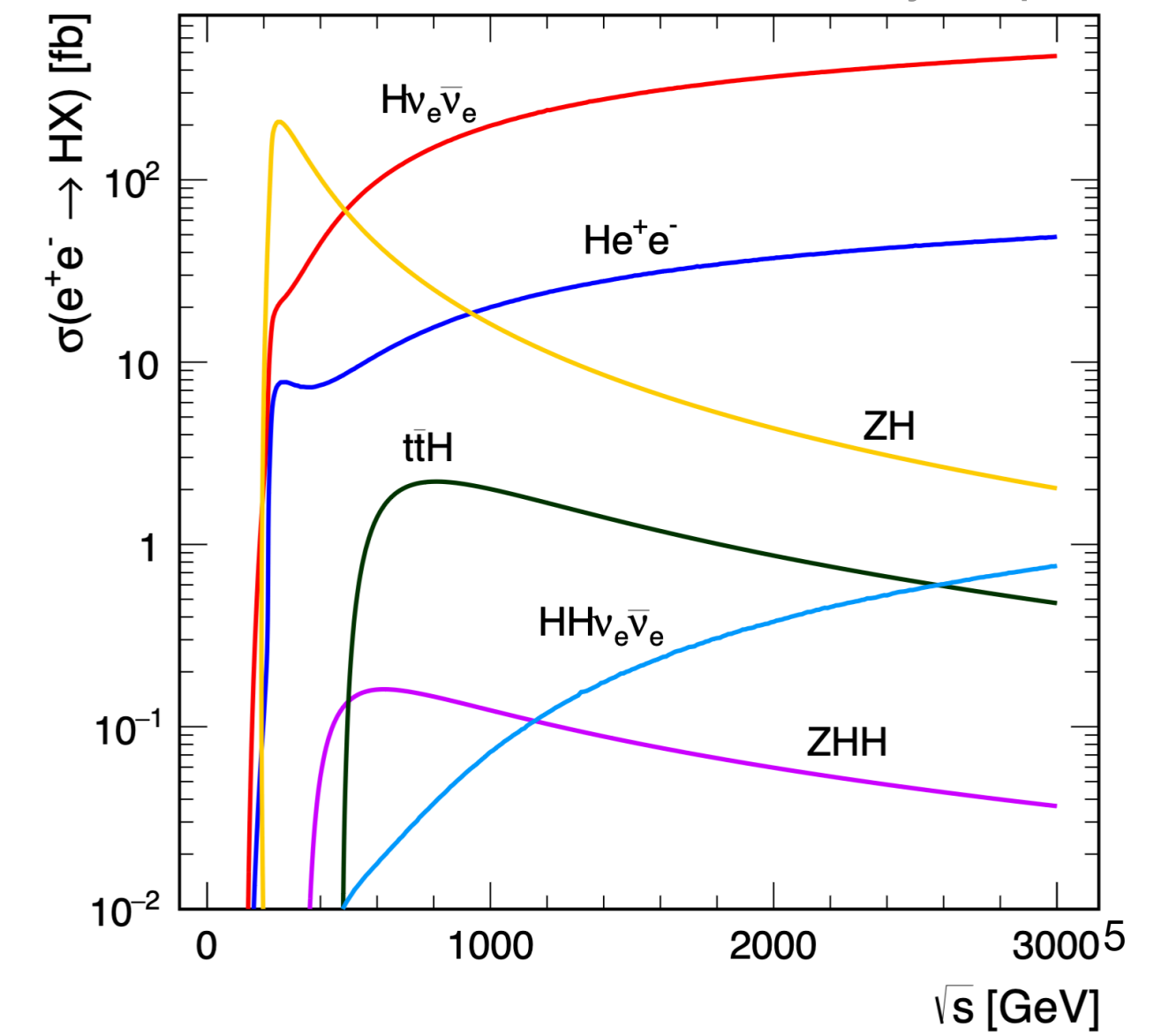
$N^5\text{LO}$ (heavy-top limit), $N^4\text{LO}$ ($m_t \neq 0$); $N^4\text{LO}$ differential, $N^3\text{LO}$ differential ($m_t \neq 0$)

Hadronic event shapes (Z, W, H decays)

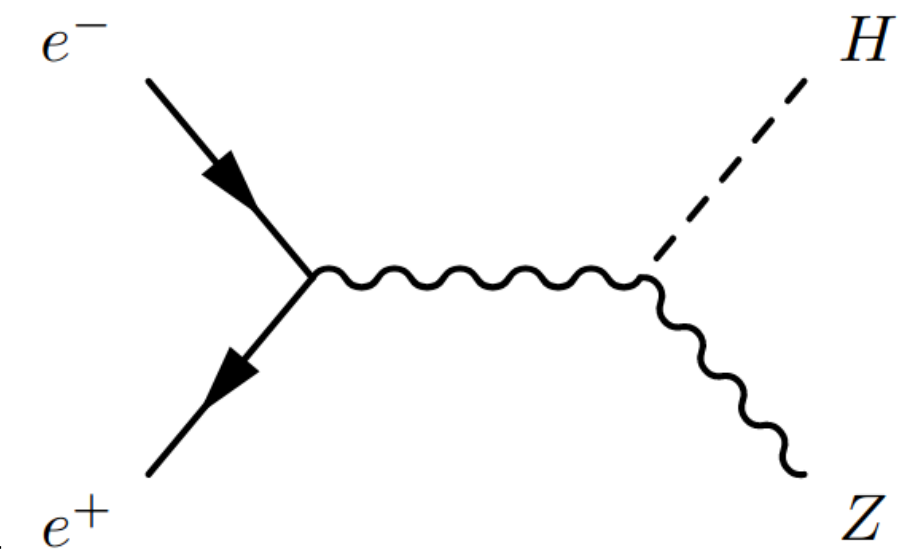
$N^3\text{LO}$ differential, $N^{3,4}\text{LL}$ resummation, power corrections

[Physics Briefing Book](#)

CLIC 2018 Summary Report



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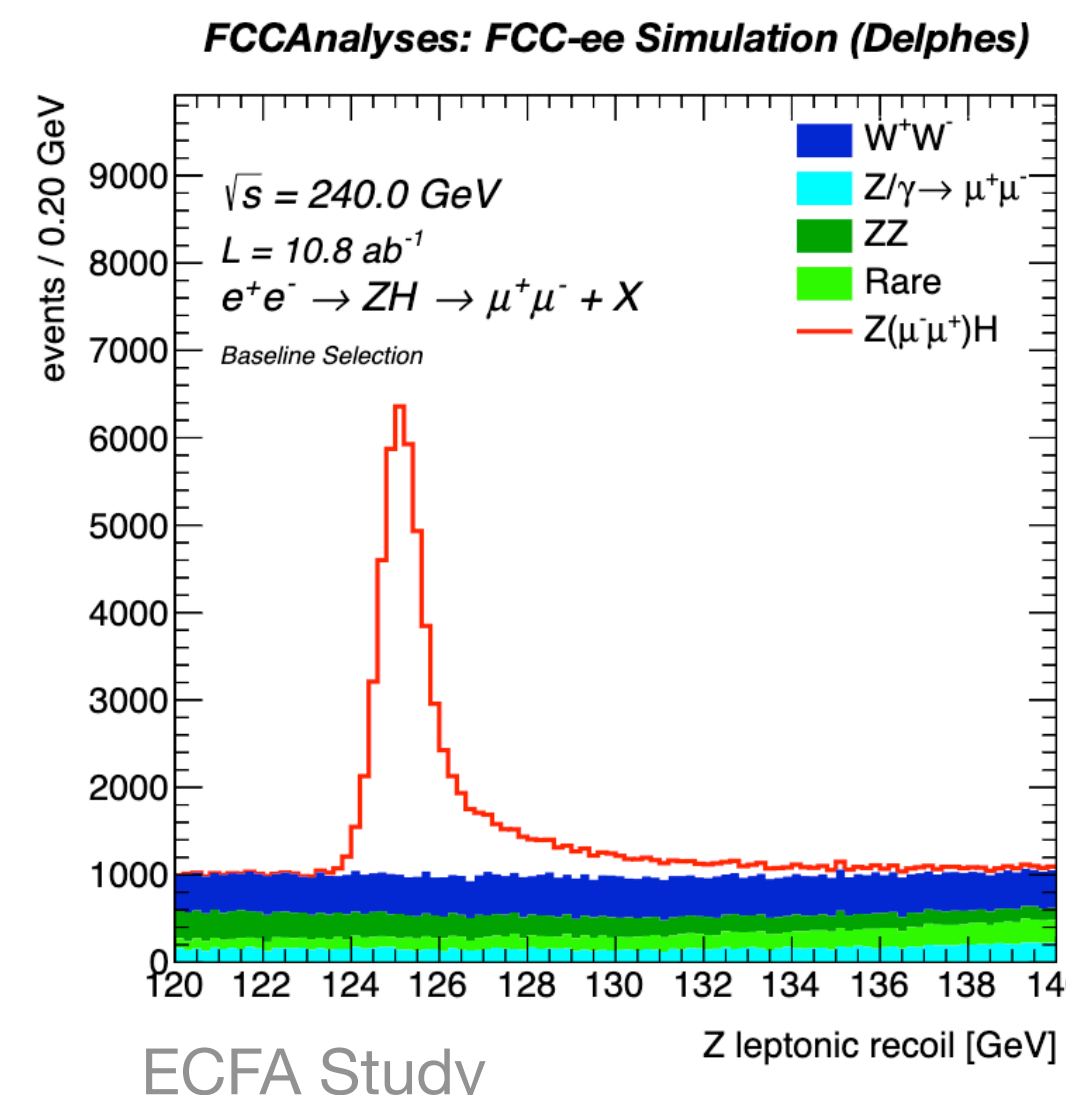
N^5 LO (heavy-top limit), N^4 LO ($m_t \neq 0$); N^4 LO differential, N^3 LO differential ($m_t \neq 0$)

Hadronic event shapes (Z, W, H decays)

N^3 LO differential, $N^{3,4}$ LL resummation, power corrections

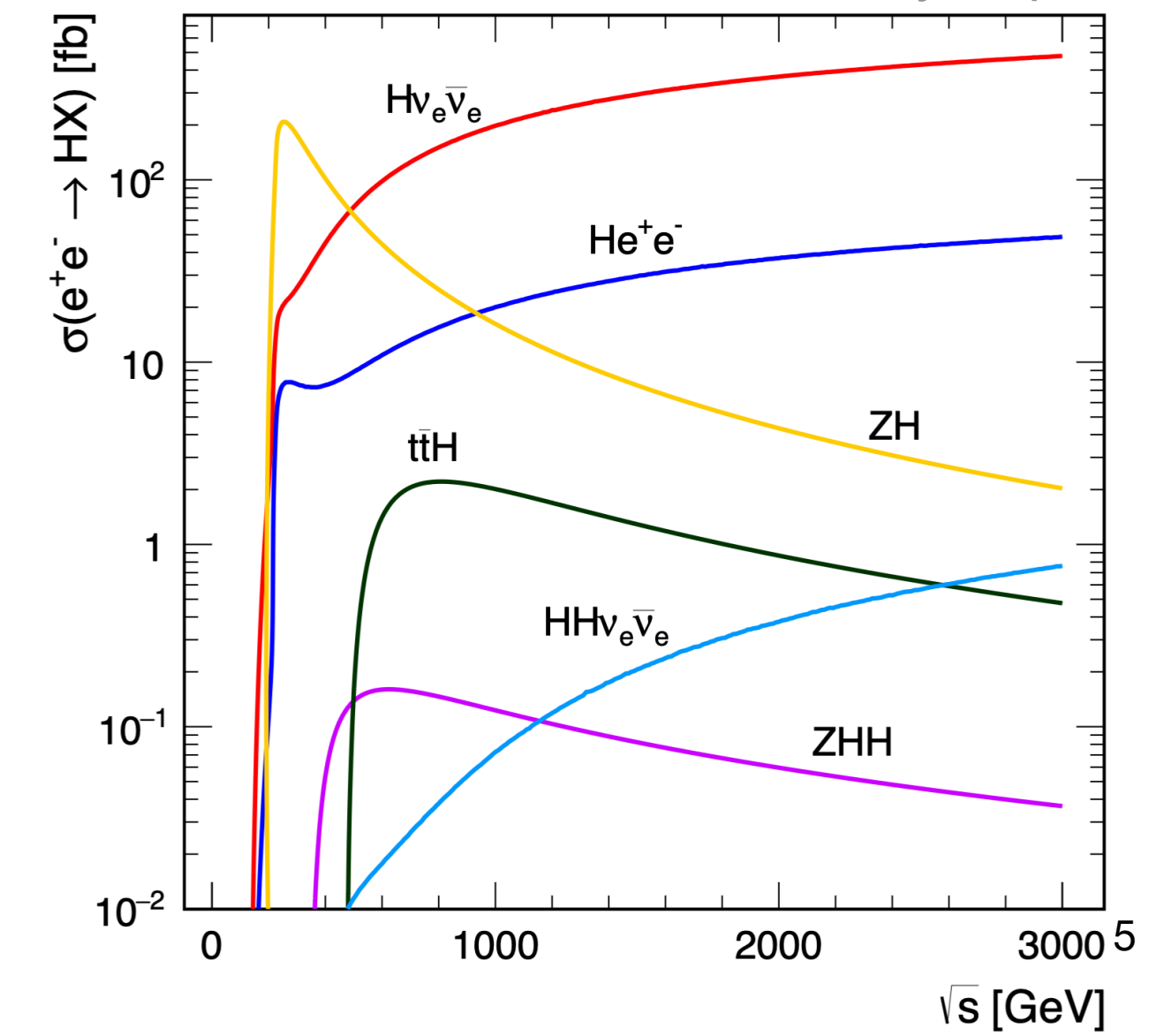
[Physics Briefing Book](#)

- Key advantage: Inclusive σ_{ZH} from recoil mass
- Turns into an absolute coupling measurement in κ framework
- Also use to measure $\delta m_H \sim 4$ MeV



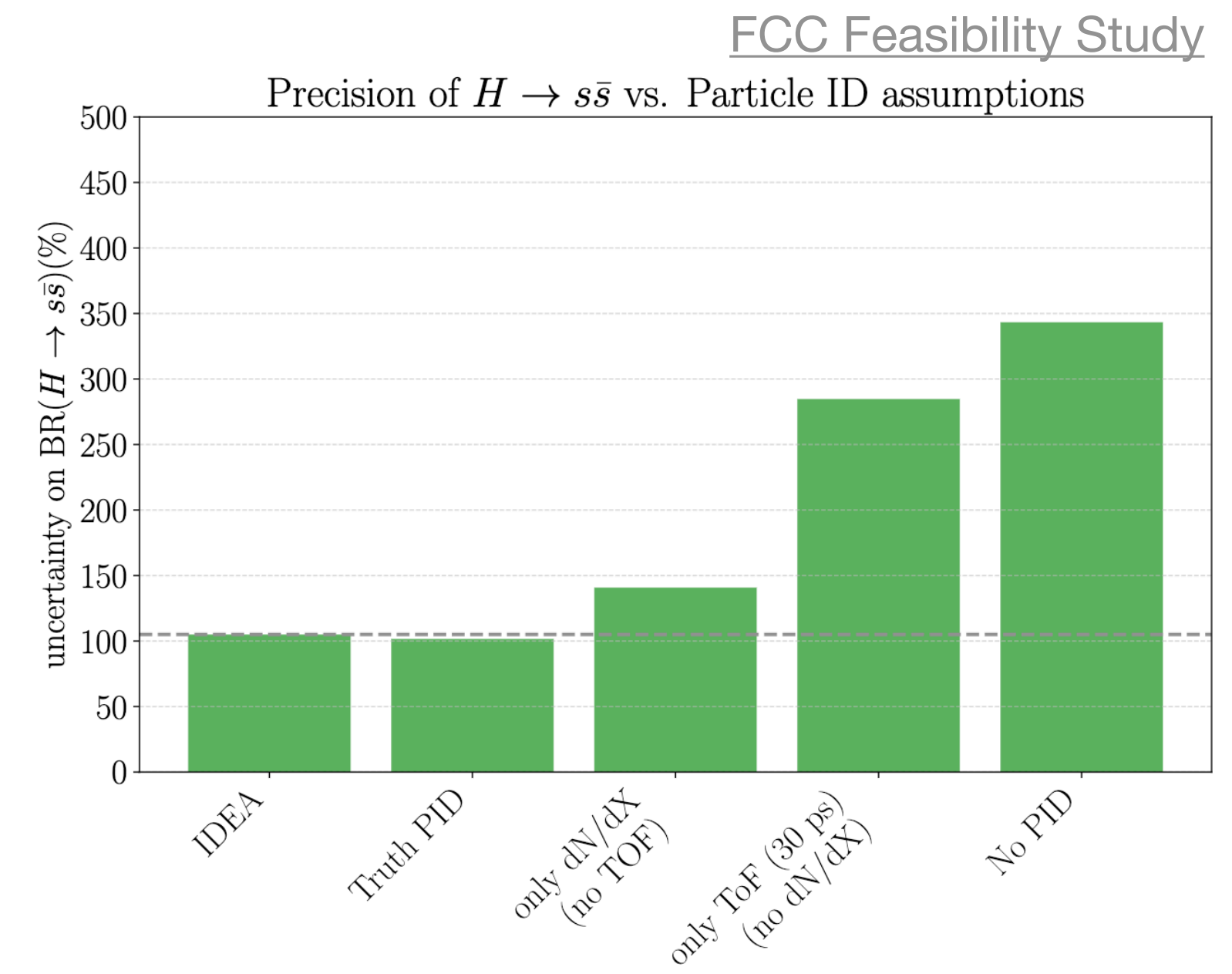
[ECFA Study](#)

[CLIC 2018 Summary Report](#)



e^+e^- Colliders: Unique Precision Opportunities

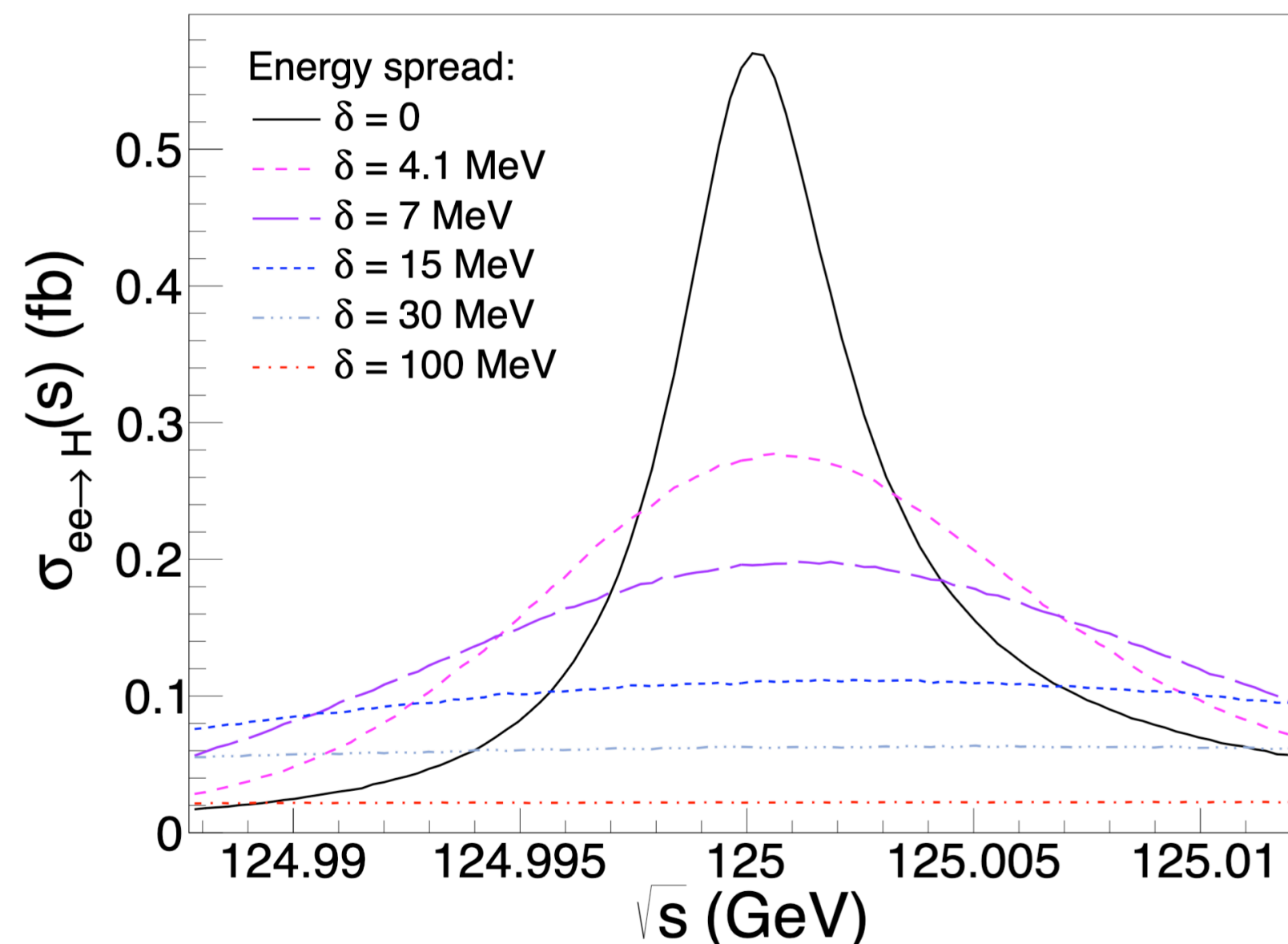
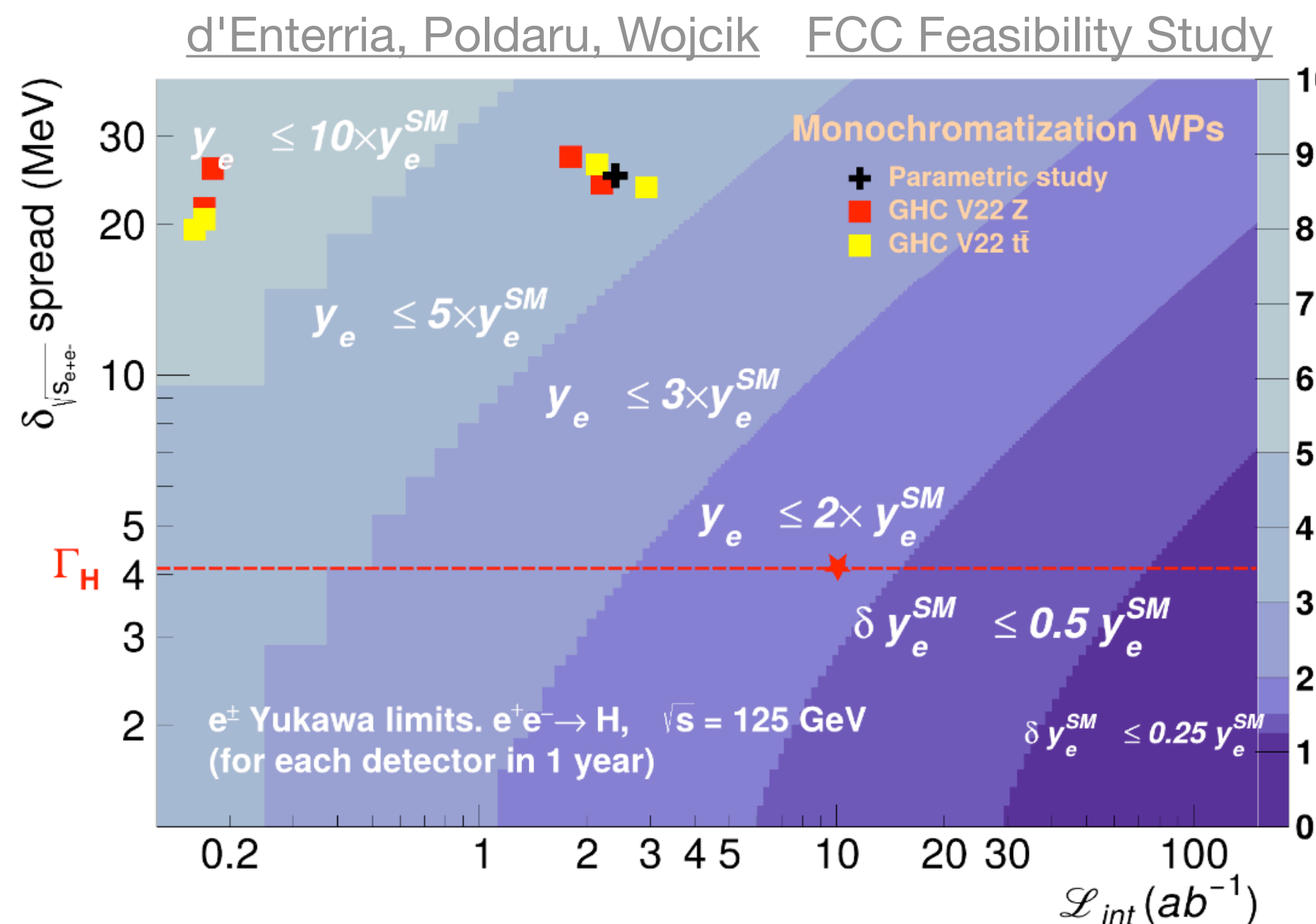
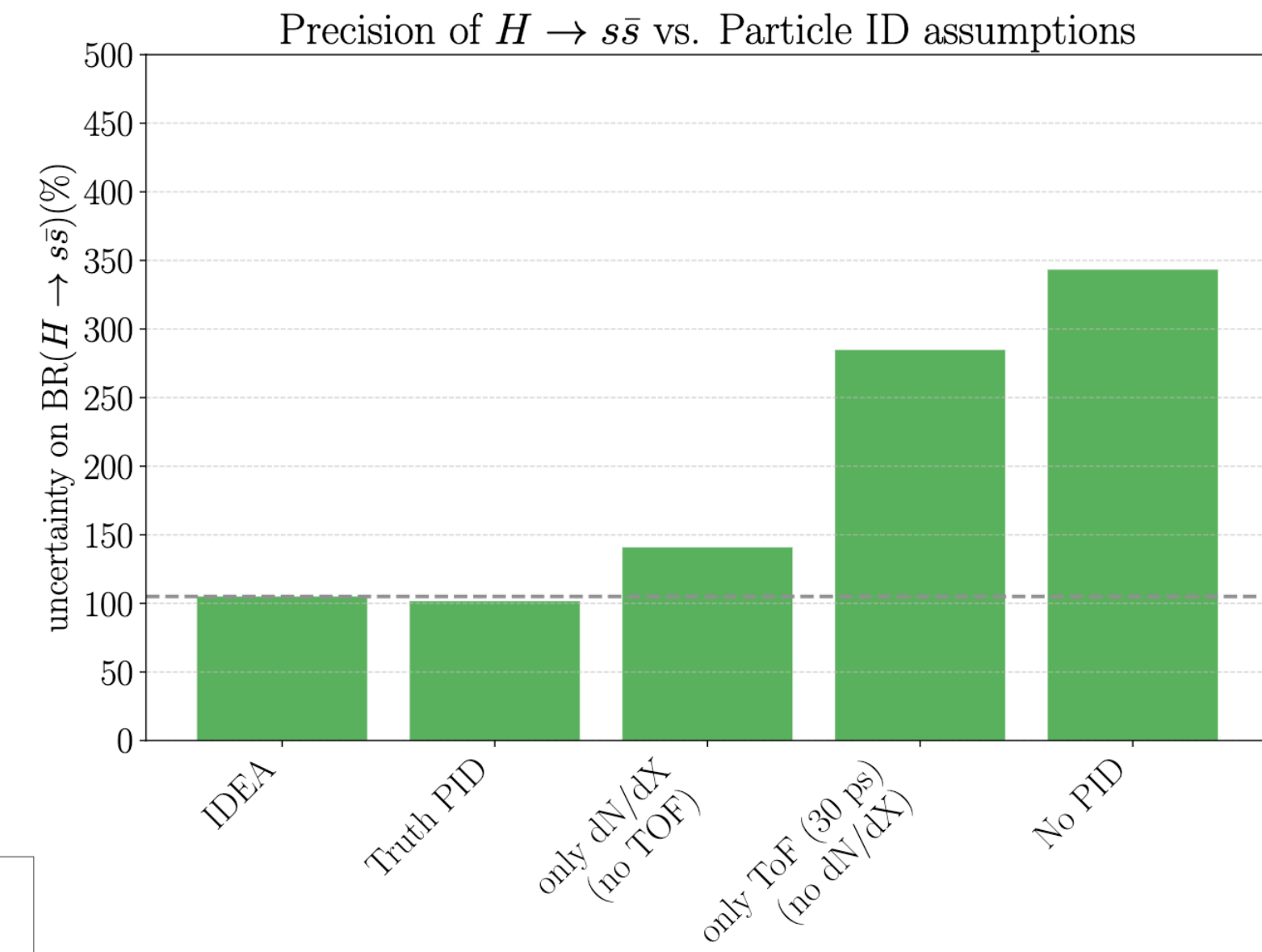
- Strange tagging: measure $H \rightarrow s\bar{s}$ to $\mathcal{O}(1)$ level



e^+e^- Colliders: Unique Precision Opportunities

- Strange tagging: measure $H \rightarrow s\bar{s}$ to $\mathcal{O}(1)$ level
- A dedicated multi-year 125 GeV run could constrain $\delta\kappa_e \sim \mathcal{O}(1)$

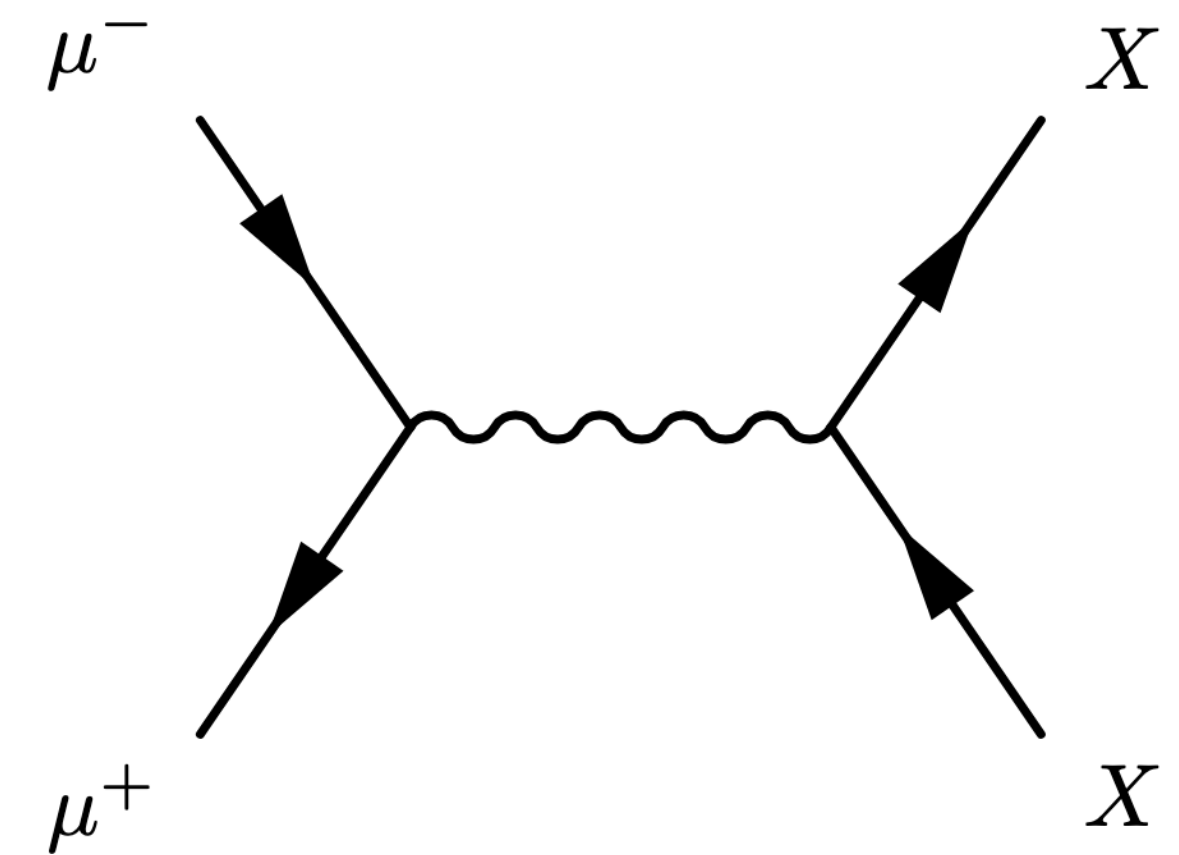
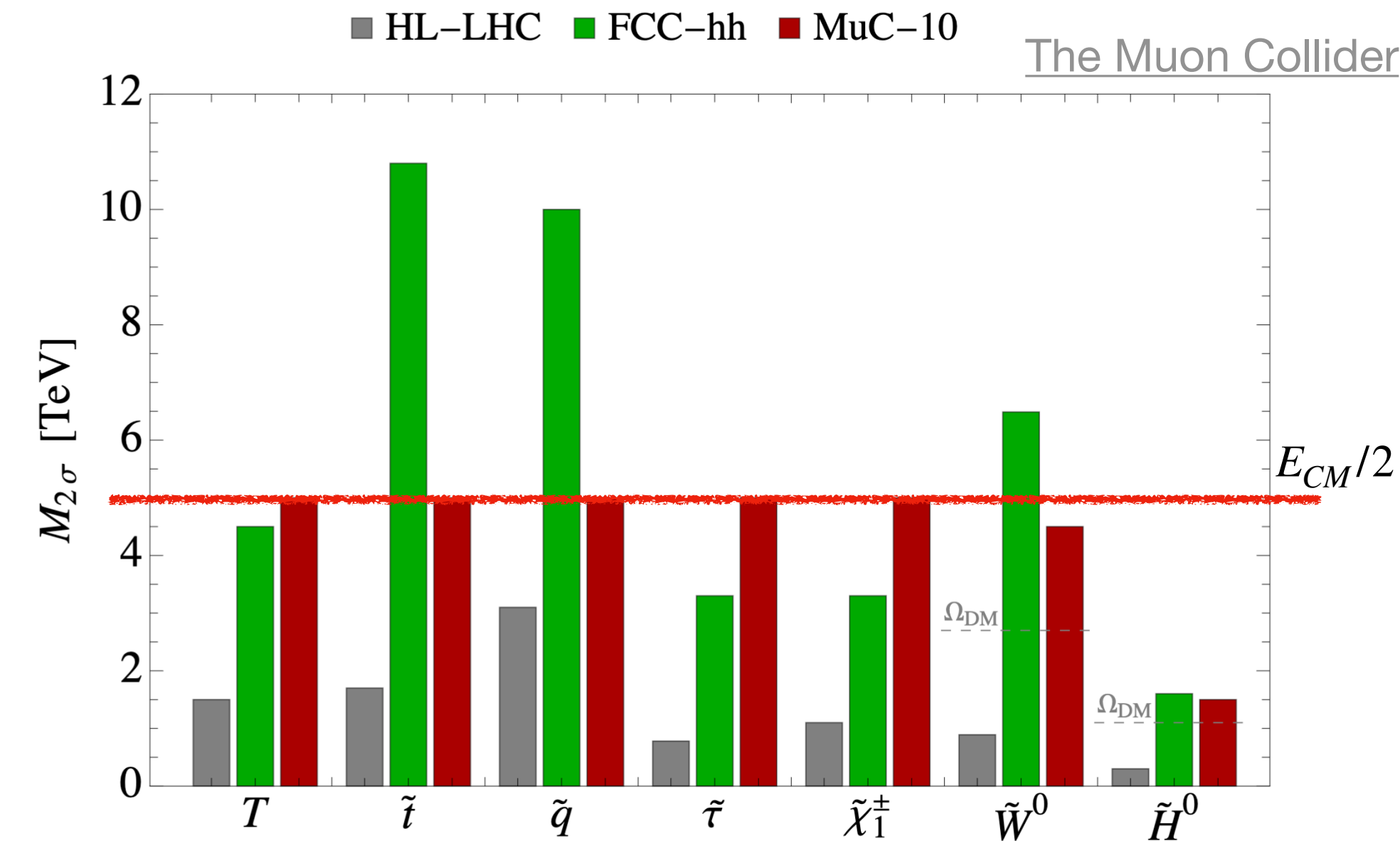
FCC Feasibility Study



Interesting aside: 125 GeV $\mu^+\mu^-$ could do this for κ_μ
de Blas, Gu, Liu

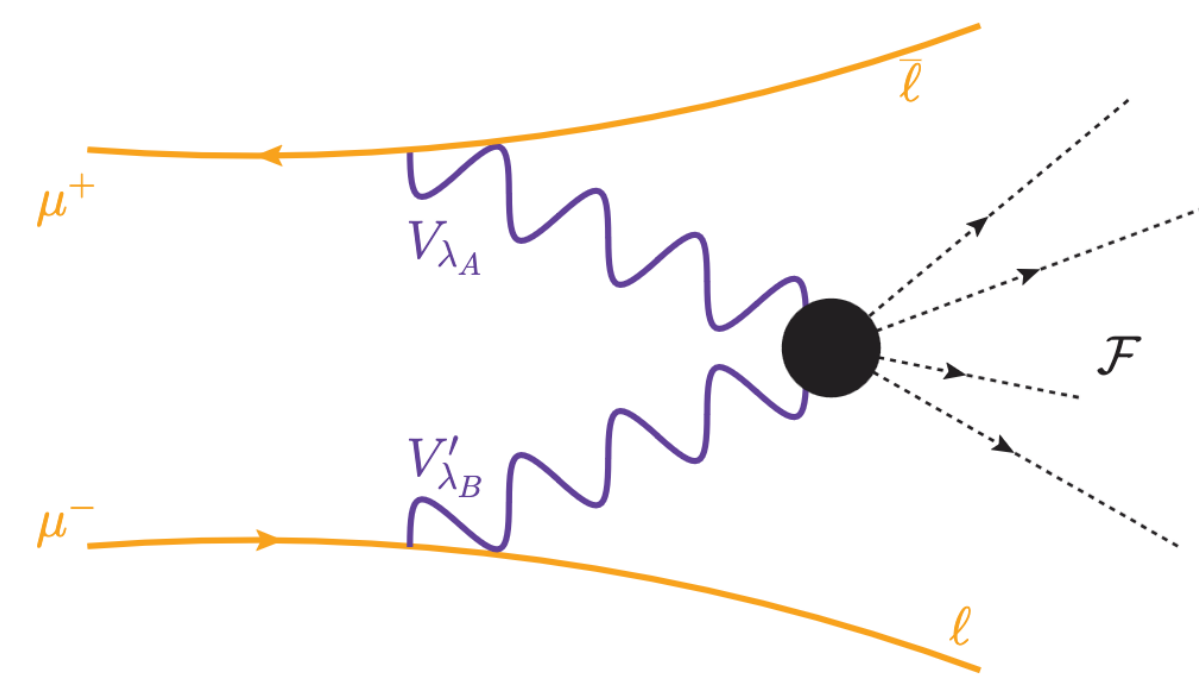
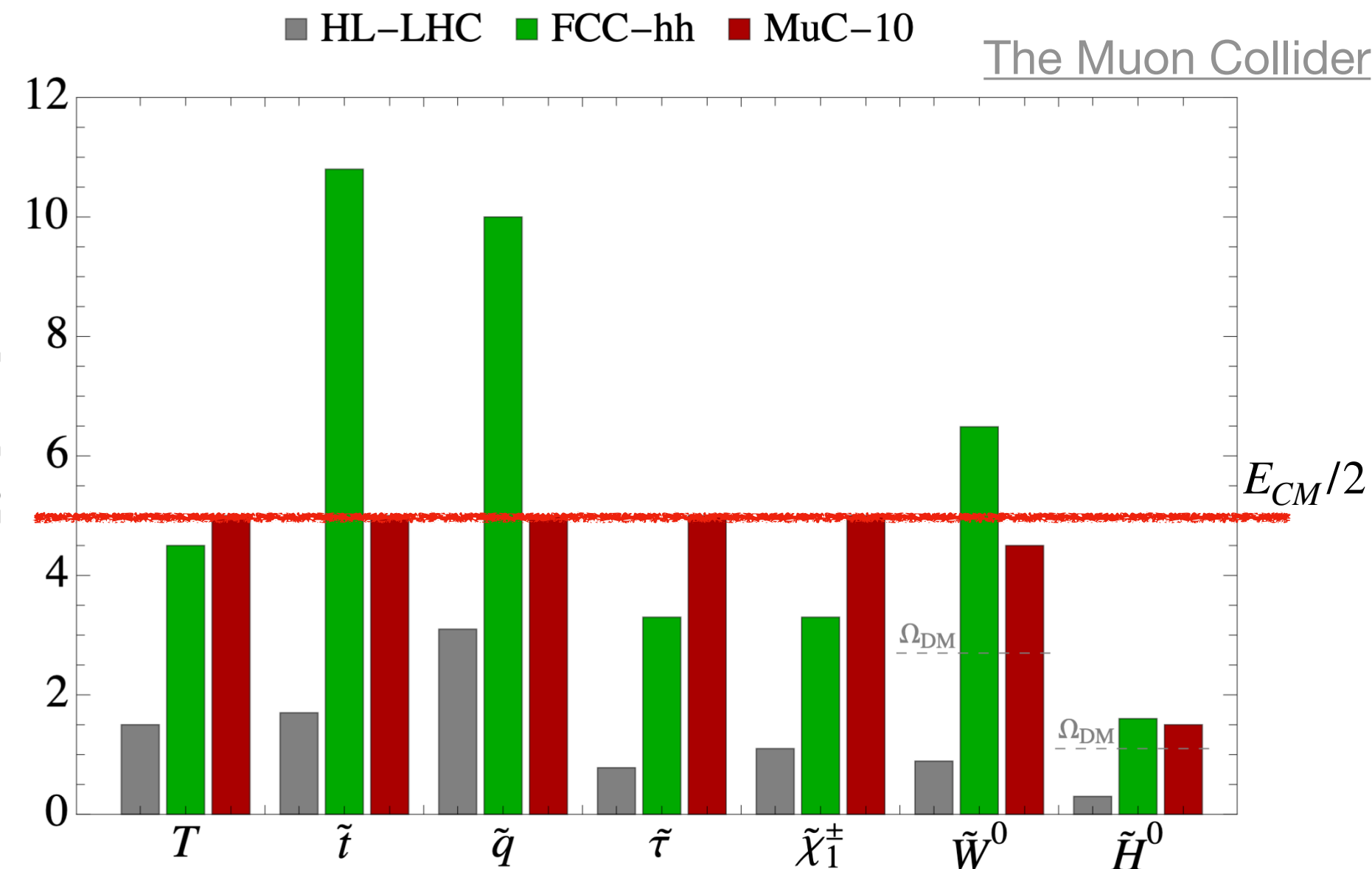
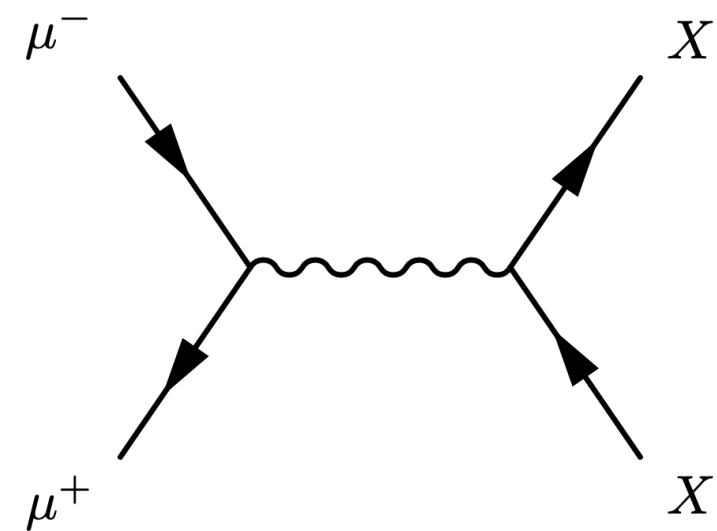
Muon Colliders

- Energy and precision in one machine
- Constrain or discover nearly any BSM coupled to EW up to $M = E_{CM}/2$

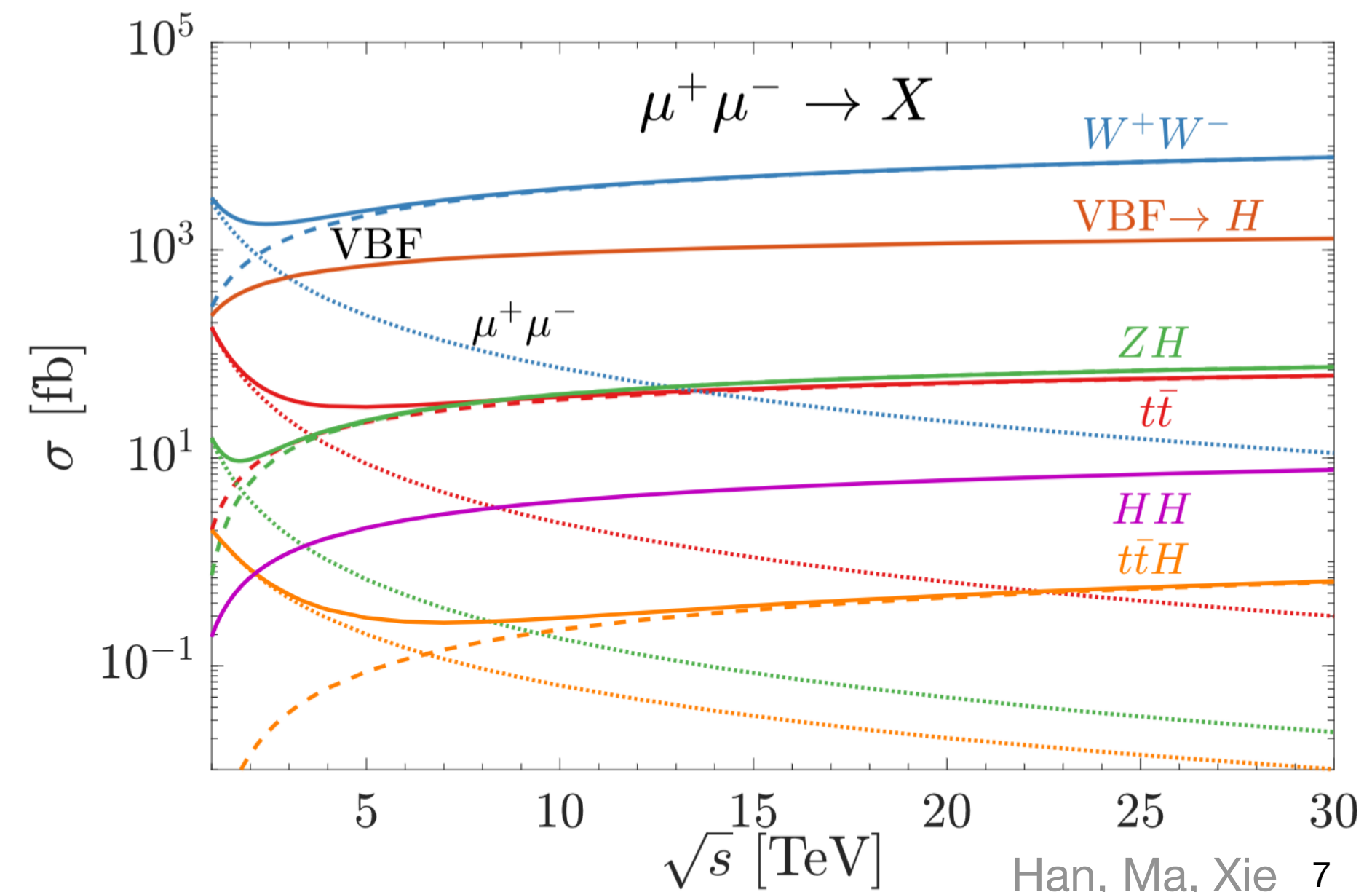
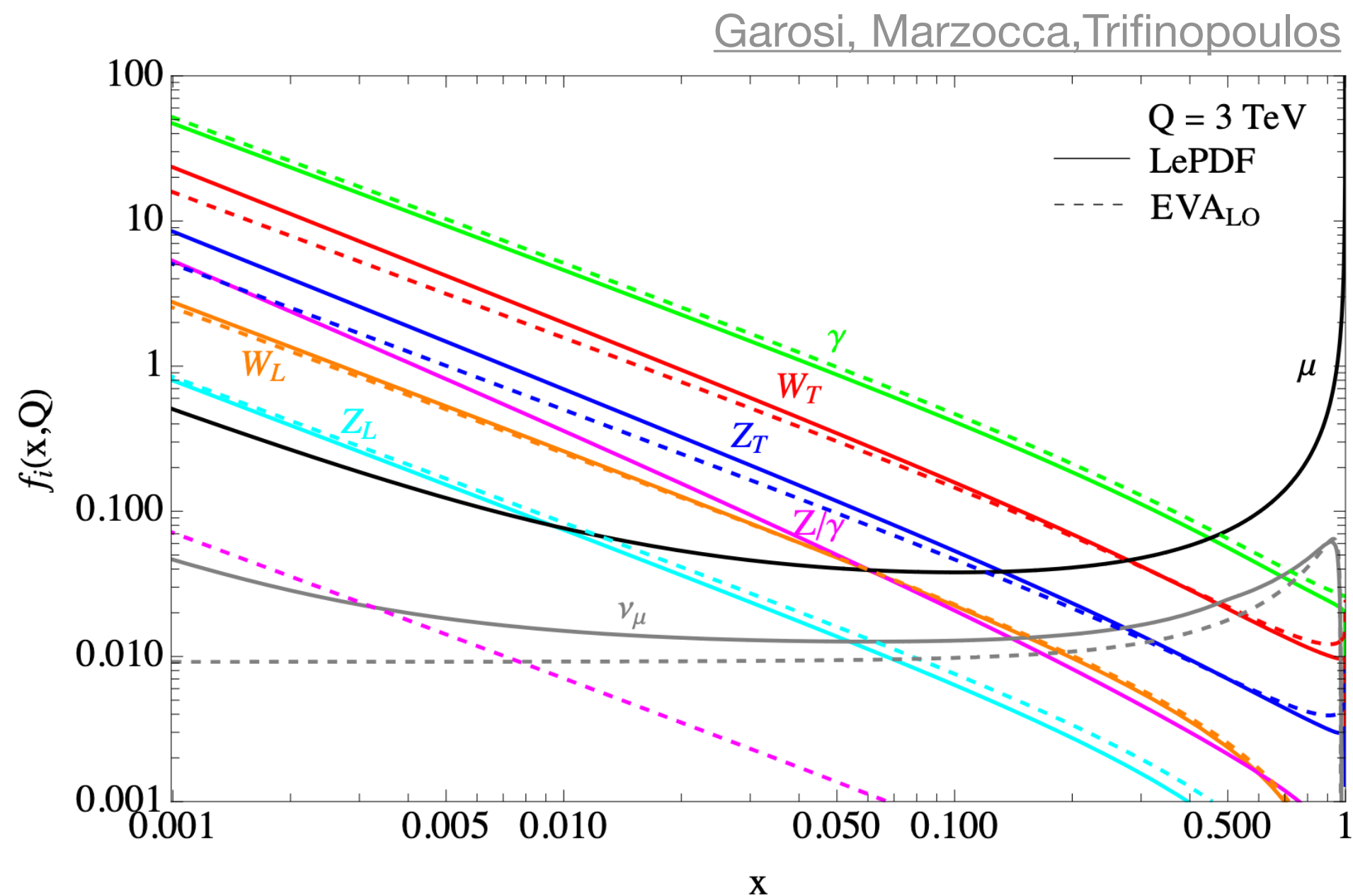


Muon Colliders

- Energy and precision in one machine
- Constrain or discover nearly any BSM coupled to EW up to $M = E_{CM}/2$
- For SM processes: muon colliders are gauge boson colliders

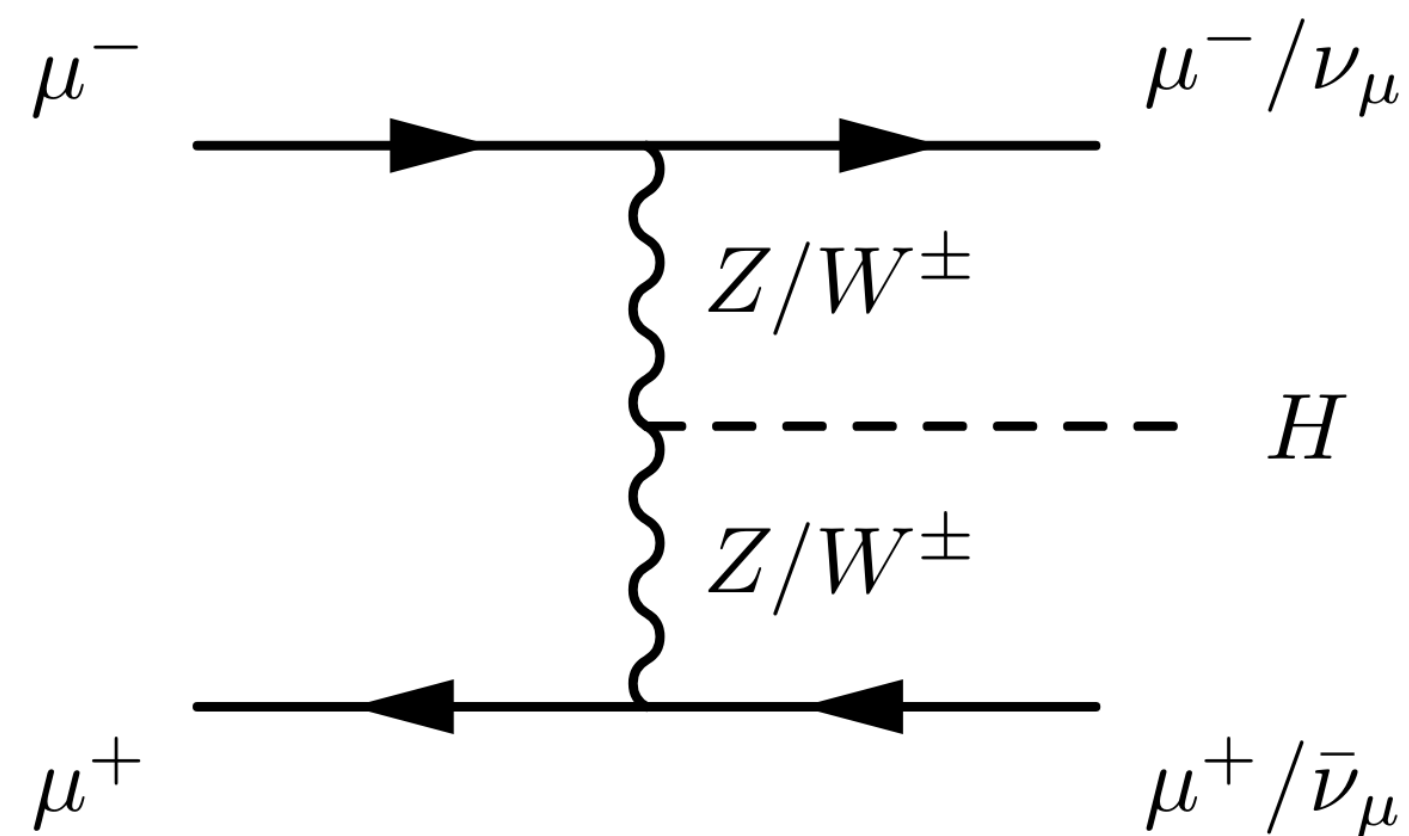


Ruiz, Costantini, Maltoni, Mattelaer

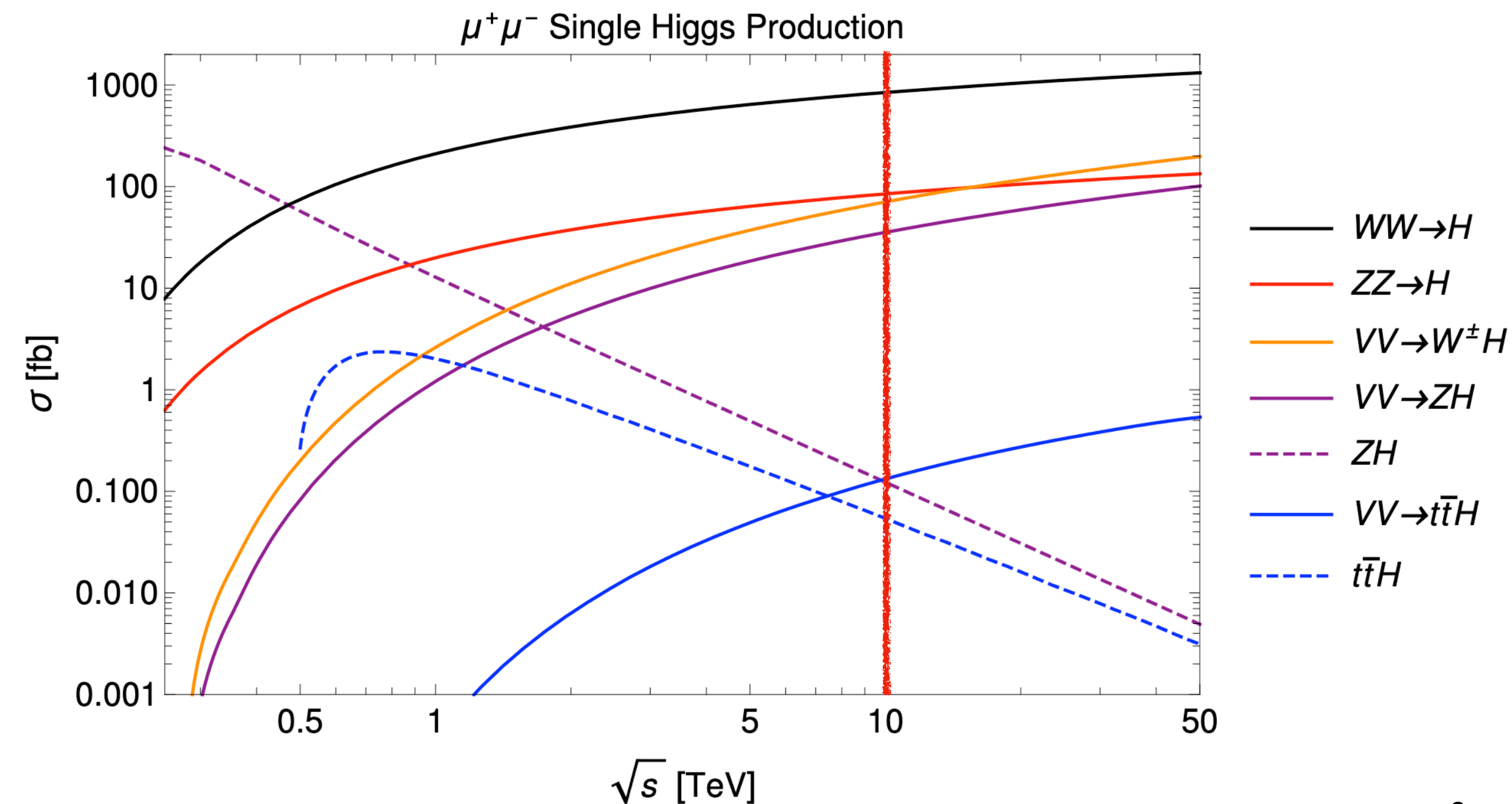


Muon Colliders

- 10/ab $\rightarrow \mathcal{O}(10^7)$ Higgses - How good is its Higgs physics program?
- For Higgs physics: 90% W^+W^- -fusion, 10% ZZ -fusion MF, Meade 2022
MF, Meade 2023



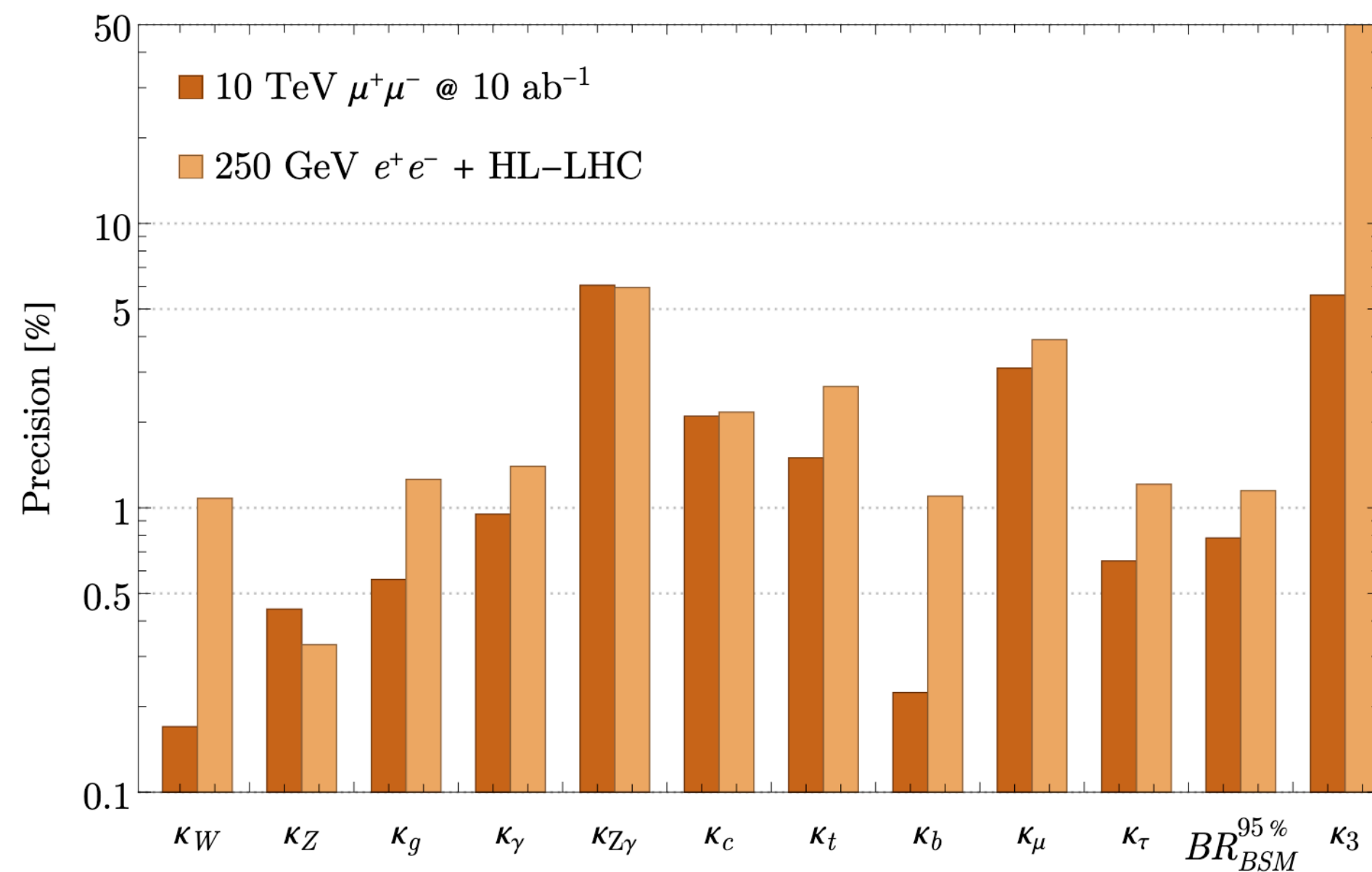
- Nearly all important SM processes are VBF - even $t\bar{t}H$



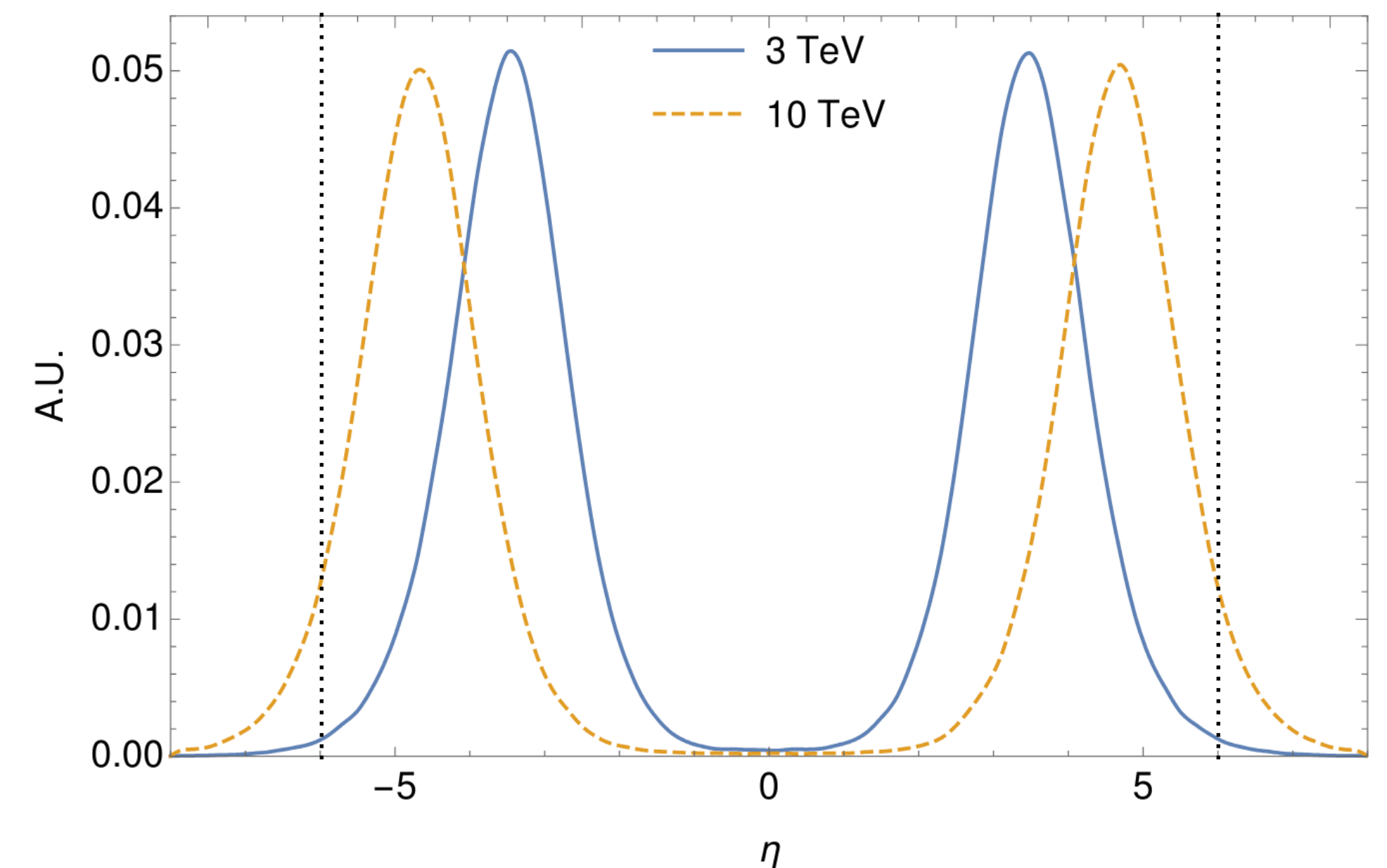
Muon Colliders

- Physics outputs depend on forward muon tagging to distinguish ZZ/WW fusion
- Width extraction requires some thought, but can be done robustly
- End conclusion: Higgs sensitivity similar to $250 \text{ GeV } ee$
- Complementarity -- different production modes than at ee

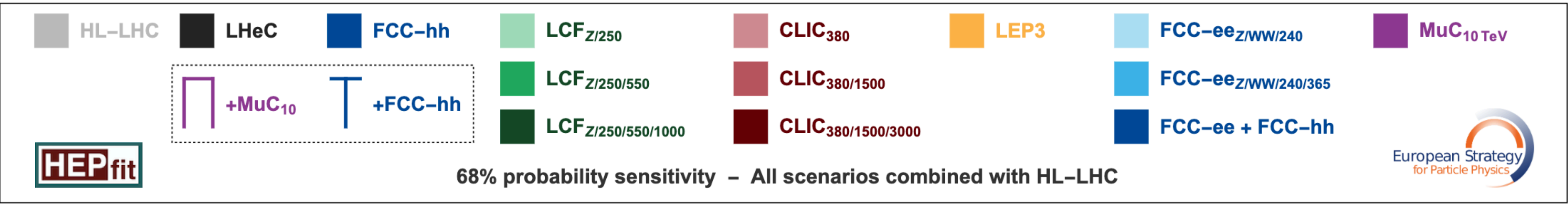
Being verified channel-by-channel in full simulation
[Muon Collider ESPP Report](#)



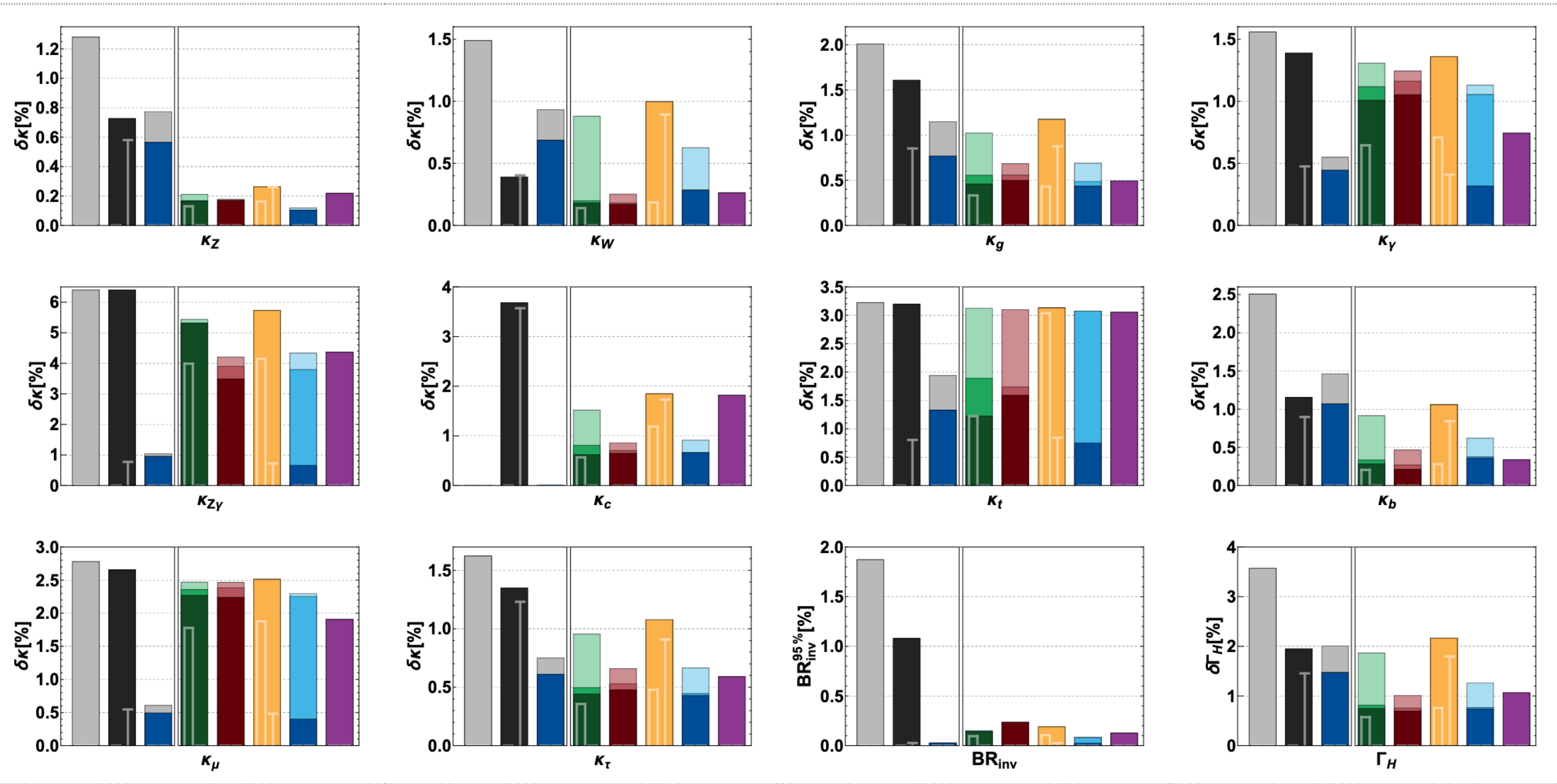
[MF, Meade 2022](#)
[MF, Meade 2023](#)



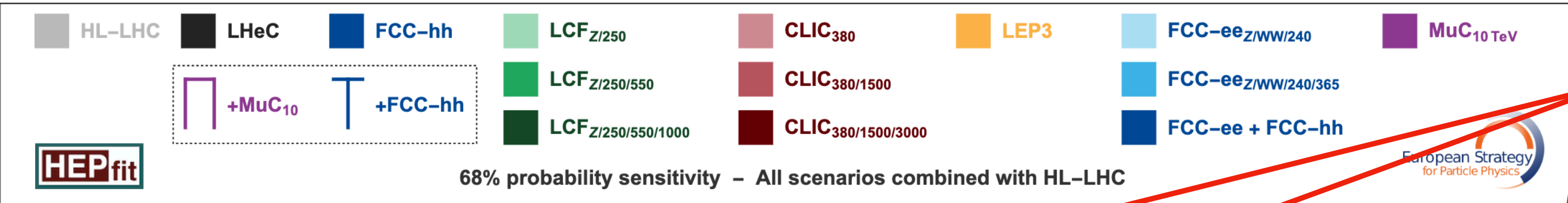
The big picture in one slide



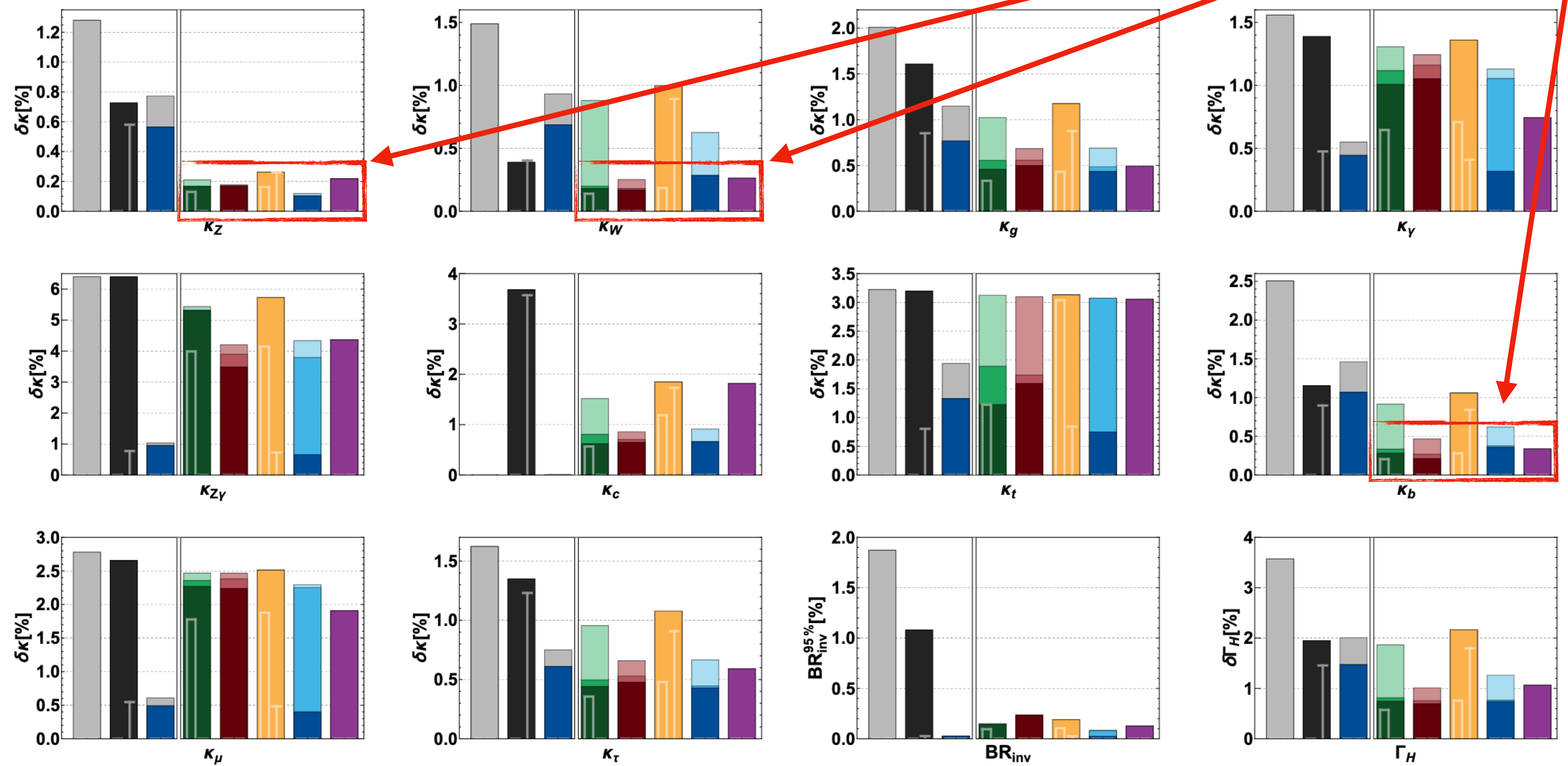
$$\kappa = g/g_{SM}$$



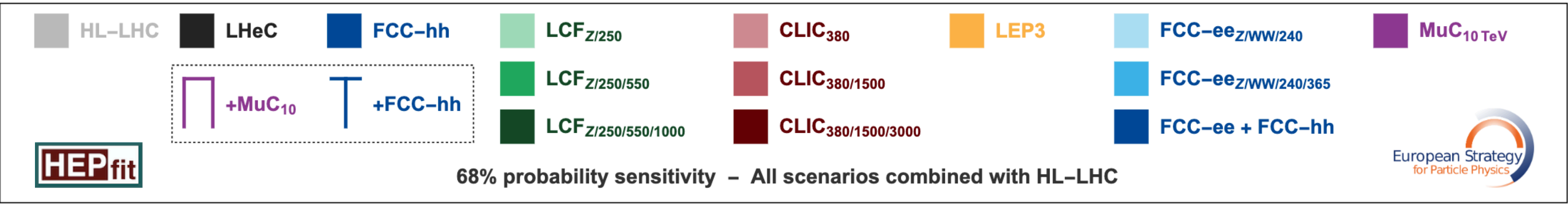
The big picture in one slide



$\sim 0.1\%$ on κ_V, κ_b

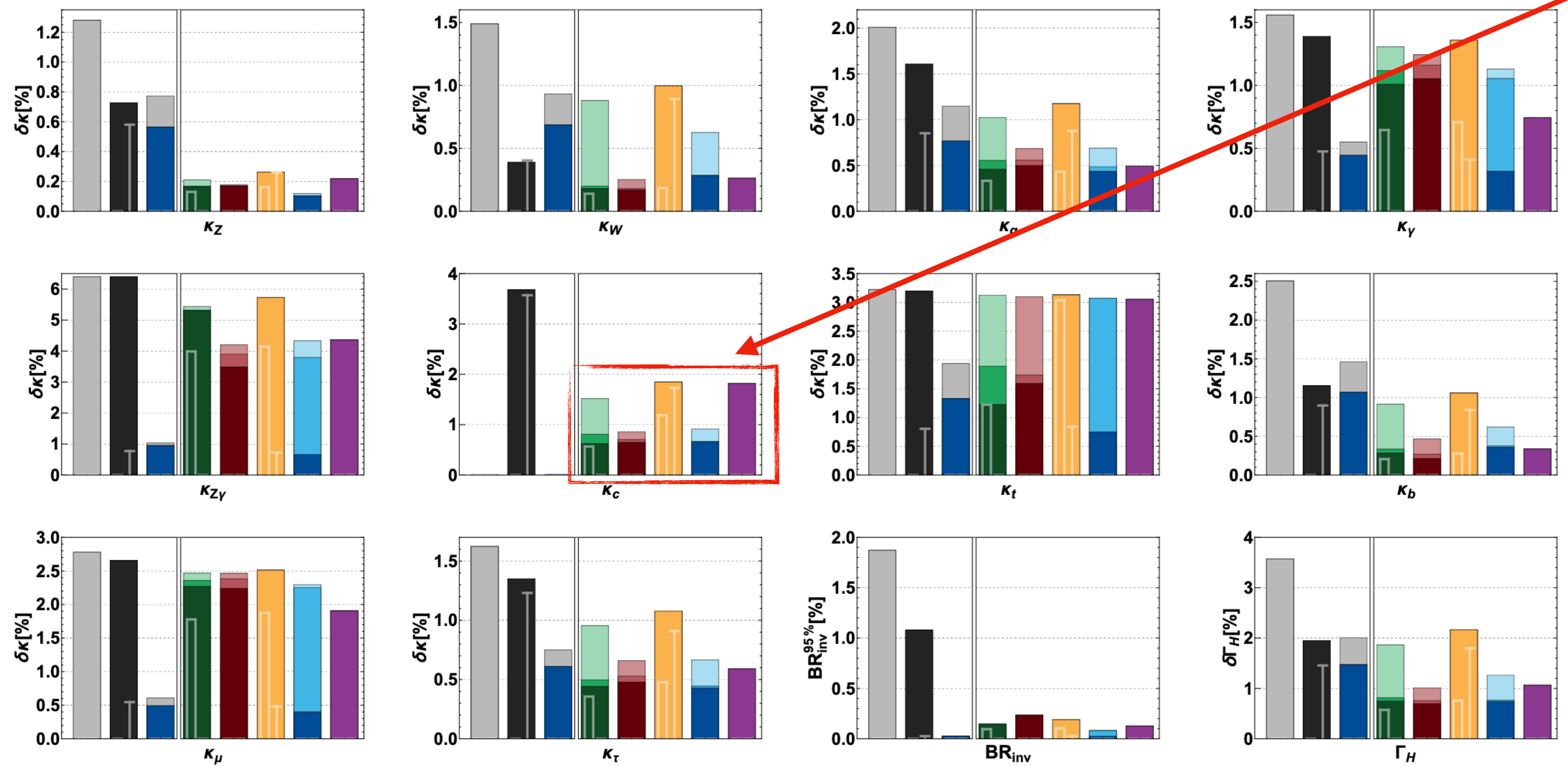


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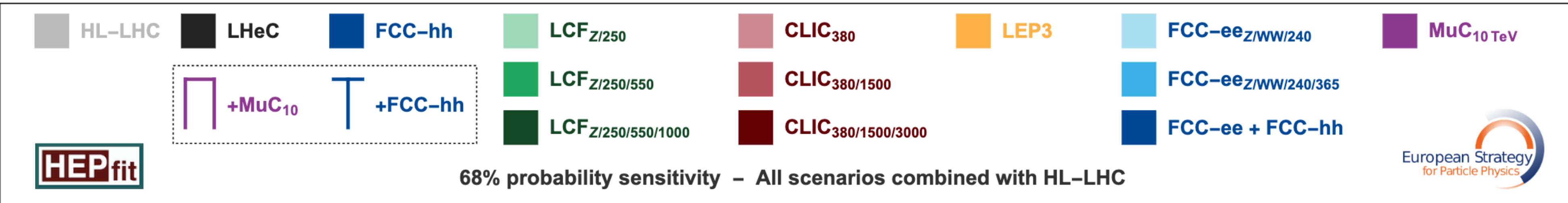


68% probability sensitivity – All scenarios combined with HL-LHC

$\sim 0.1\%$ on κ_V, κ_b
 $\sim 1\%$ on κ_c



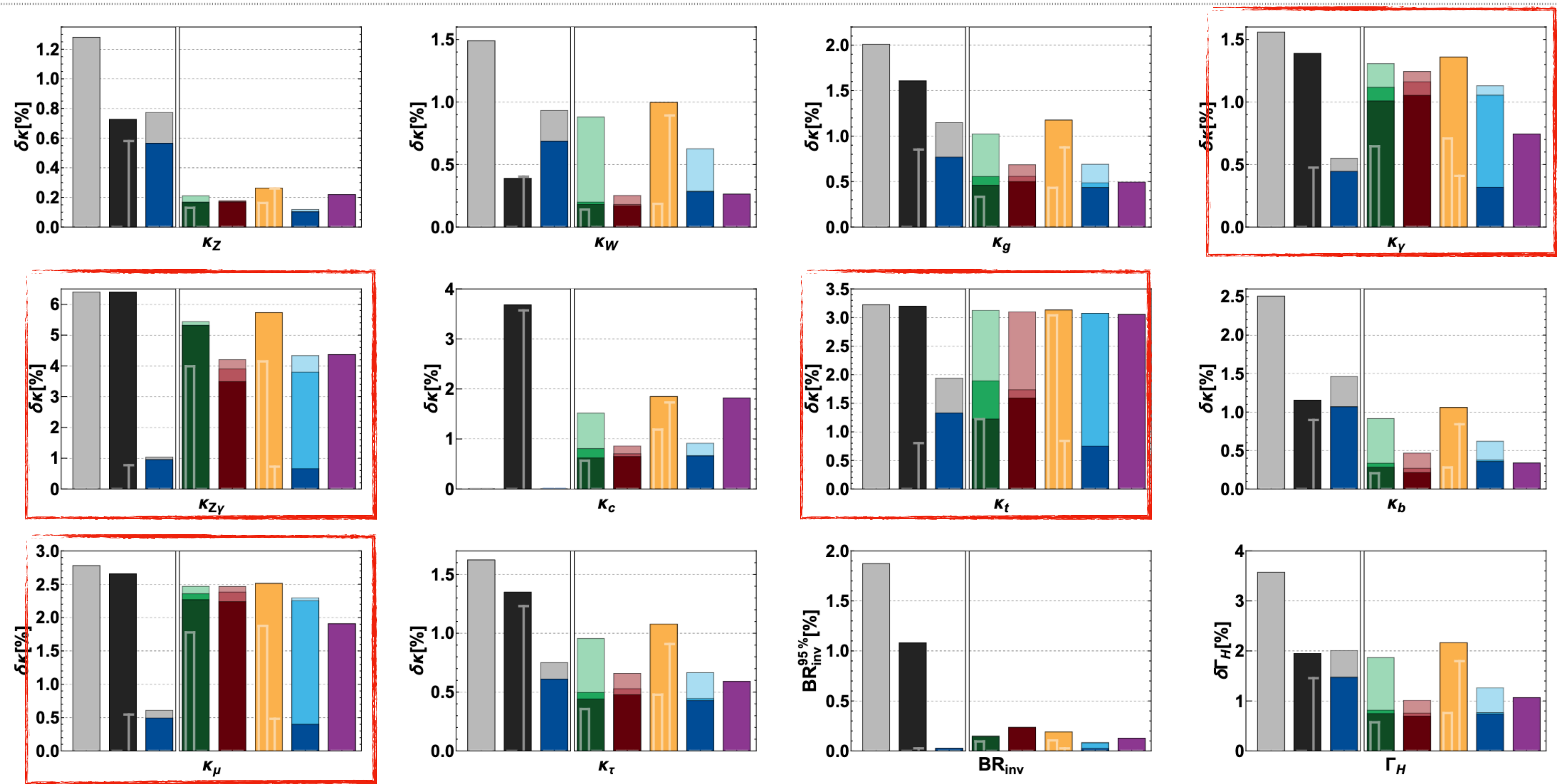
The big picture in one slide



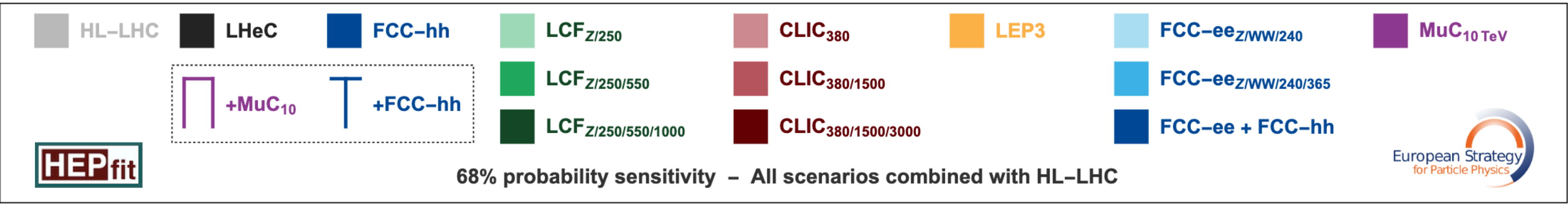
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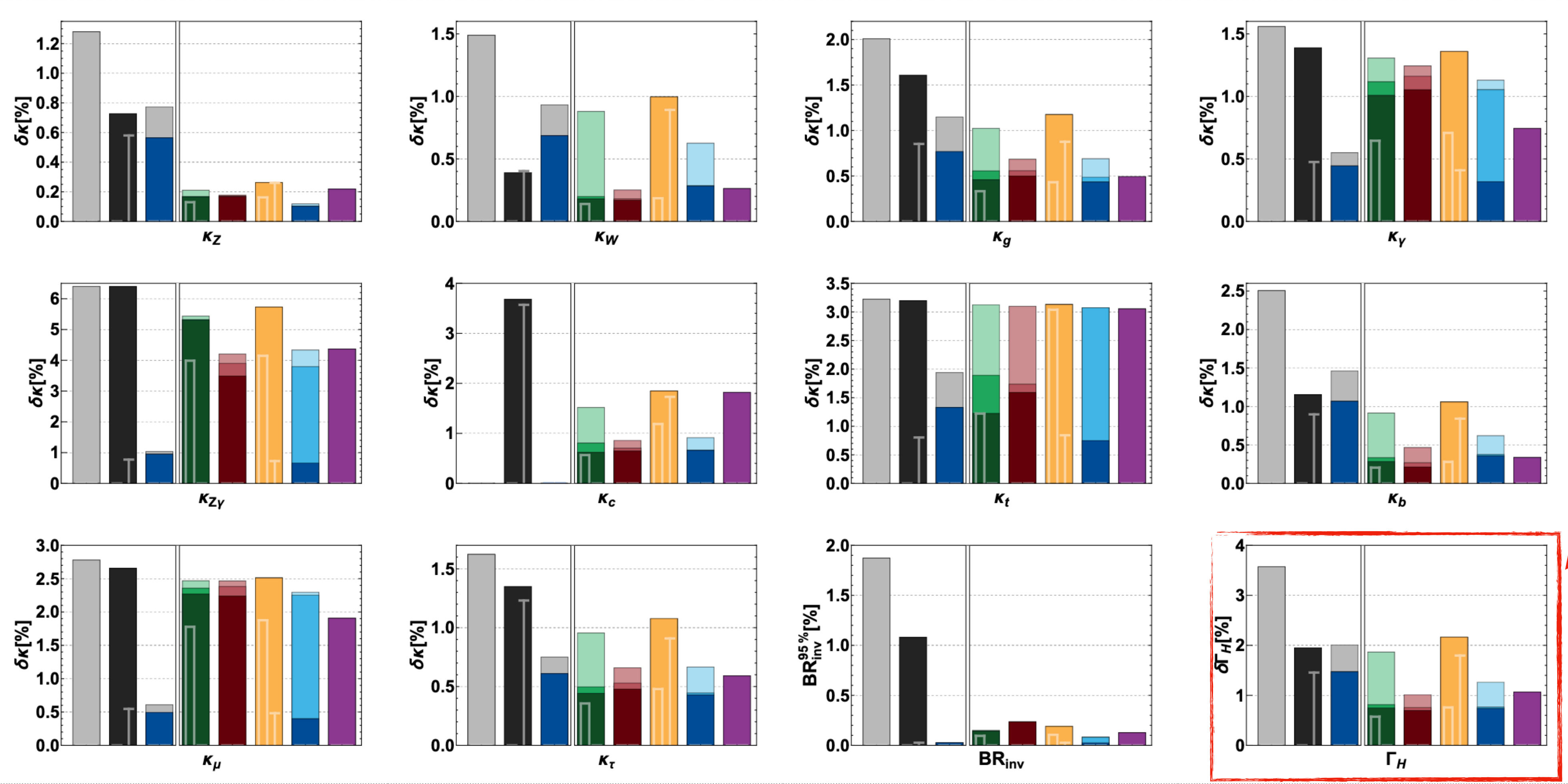
Clean rare decays and κ_t : pp wins



The big picture in one slide



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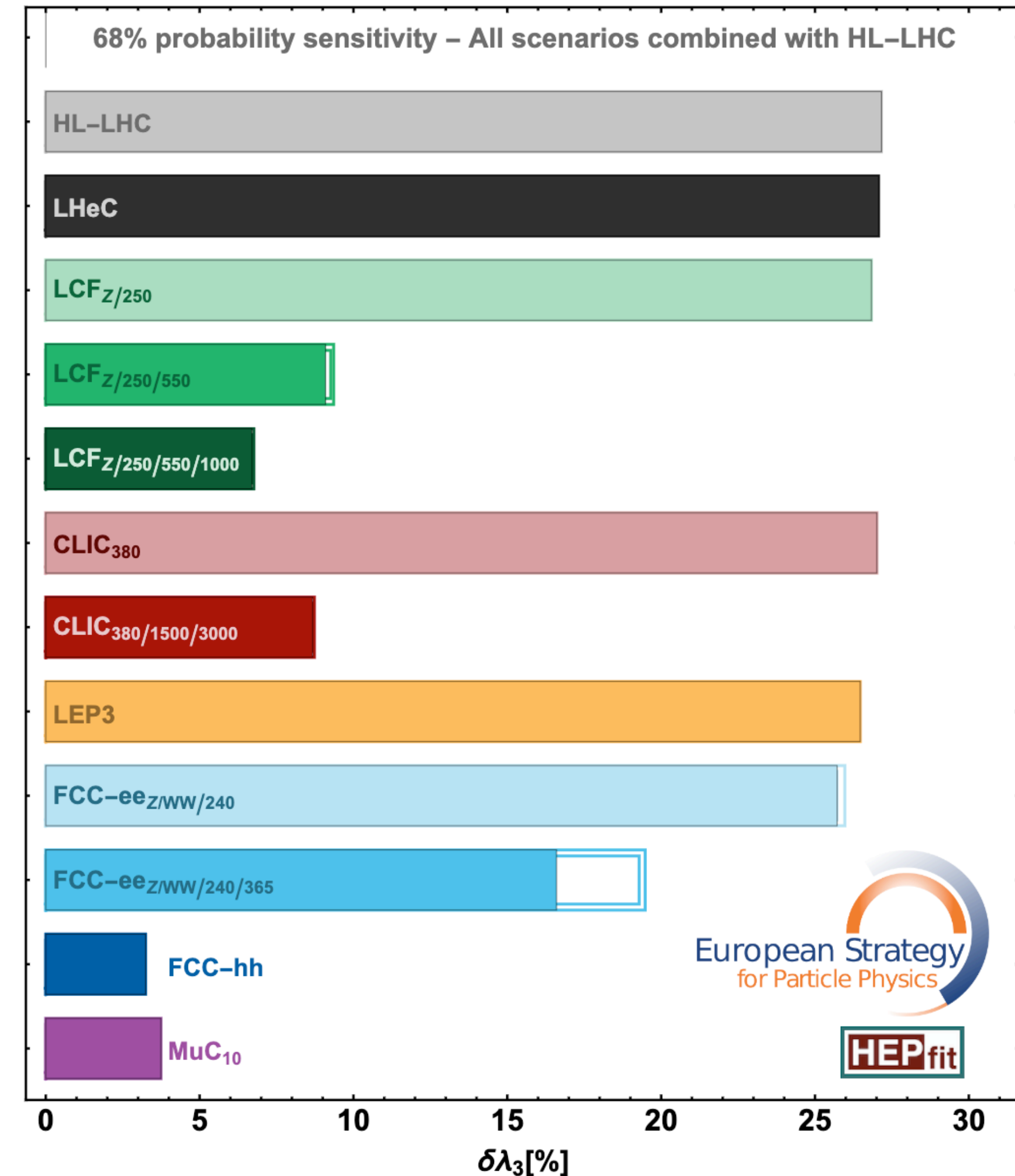


Clean rare decays
 and κ_t : pp wins
 $\Gamma_H \sim 1\%$ (fewer assumptions)

Higgs Self Coupling

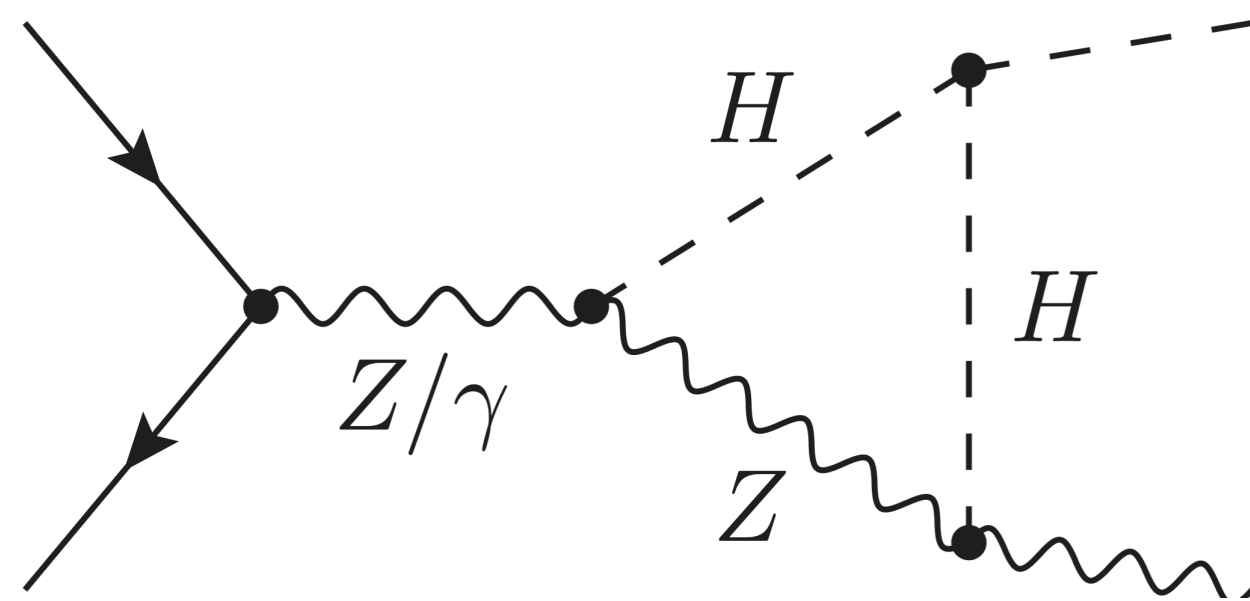
- Biggest takeaway: HL-LHC is hard to beat!
- Direct measurement at e^+e^- collider requires $E_{CM} \gtrsim 500$ GeV ($e^+e^- \rightarrow Zh h$)
- FCC-ee constraint from loop-induced effects
- MuC measurement uses VBF $VV \rightarrow hh$
- FCC-hh or MuC necessary to get $\mathcal{O}(5\%)$

From 2026 European Strategy



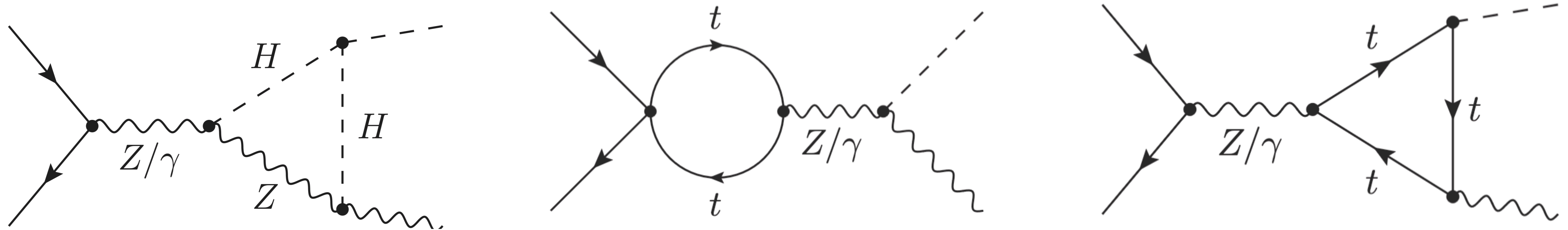
Beyond Kappas

- κ -framework doesn't tell the whole story even for couplings
- Example: Higgs self-coupling at FCC-ee:



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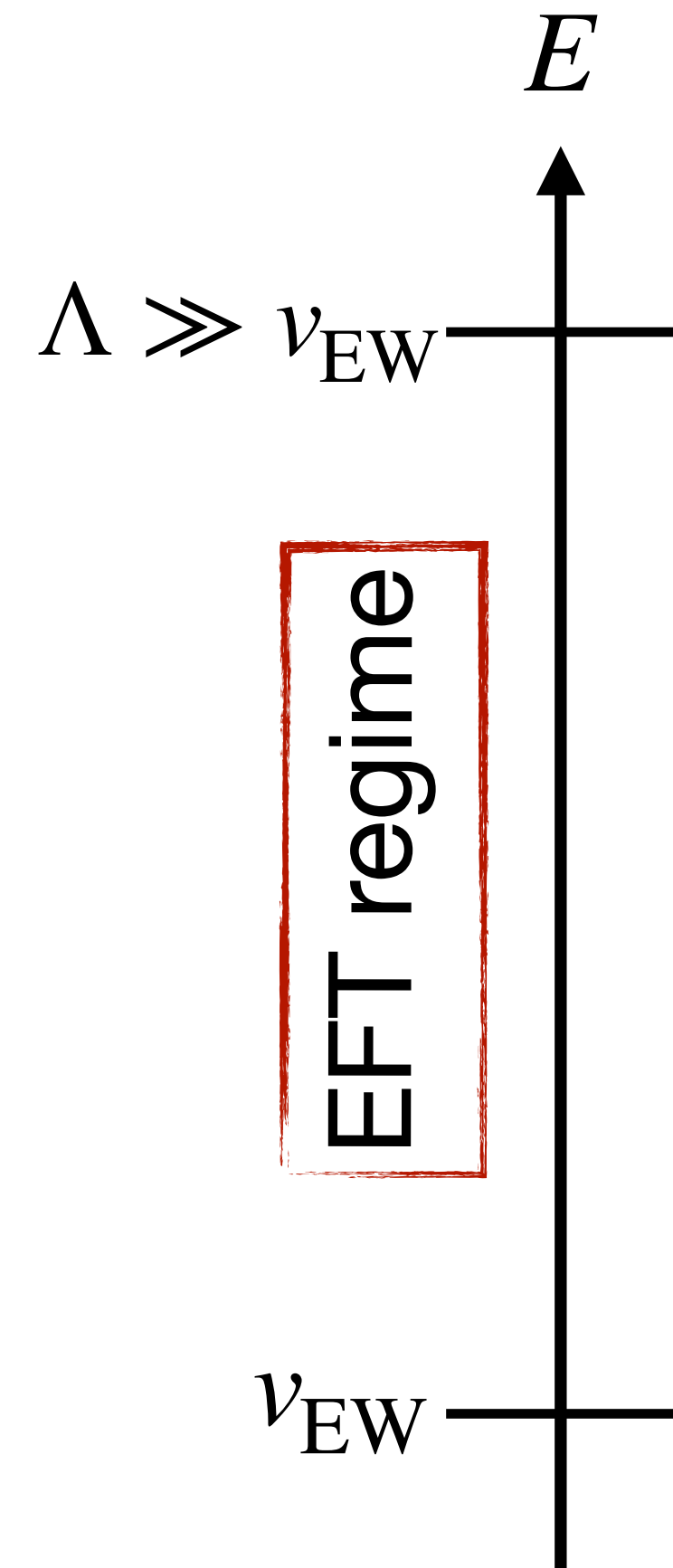
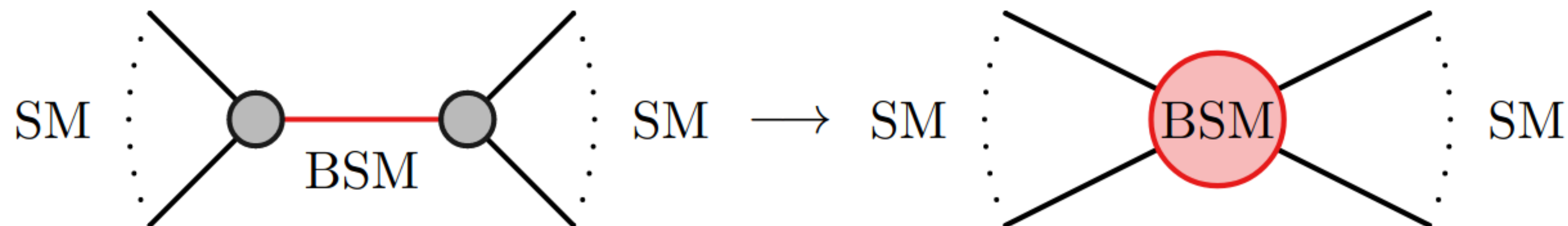
- In general, can't turn on only κ_3 at one-loop. Need to consider other loop-induced processes!
- SMEFT is the natural framework to do this consistently

SMEFT

- Assuming new physics is heavy, can integrate it out and use EFT:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- 2500 operators in general, but diagonal CKM reduces to $\mathcal{O}(200)$ in practice
- Provides a powercounting based bottom-up approach for NP
- Systematically improvable in loops and Λ
- At e^+e^- colliders, no worries about EFT validity, unitarization, etc



Going to 1-loop in the SMEFT

- At a given order in Λ , can compute arbitrary SM loops

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \frac{1}{\Lambda^2} \mathcal{M}_{\text{EFT}}^{(0)} + \frac{1}{(4\pi)^2 \Lambda^2} \mathcal{M}_{\text{EFT}}^{(1)} + \dots$$

- QCD corrections fully automated in MadGraph [Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang 2021](#)
- Electroweak corrections still must be done process-by-process
- State of the art for EWPO already include these
- For Higgs: many interesting operators enter first in EW corrections – i.e. C_ϕ

Going to 1-loop in the SMEFT

- Inputs: G_F , m_W , m_Z , α_S , m_h , m_t , and additional m_f for $H \rightarrow f\bar{f}$
- On-shell renormalization for SM params, $\overline{\text{MS}}$ for SMEFT coefficients

$$C_i(\mu) = C_{0,i} - \frac{1}{2} \left[\frac{1}{\epsilon} \bar{\mu}^{2\epsilon} \right] \frac{1}{16\pi^2} \gamma_{ij} C_j(\mu) \qquad \frac{dC_i(\mu)}{d \ln \mu} = \frac{1}{16\pi^2} \gamma_{ij} C_j(\mu)$$

- For bottom up constraints on $C_i(\mu)$, this is everything.
- For top-down constraints on explicit models, need to match at $\mu = \Lambda$ and run
- Fully NLO accurate constrains require 2-loop RGE's: recently available!

Born, Fuentes-Martín, Thomsen

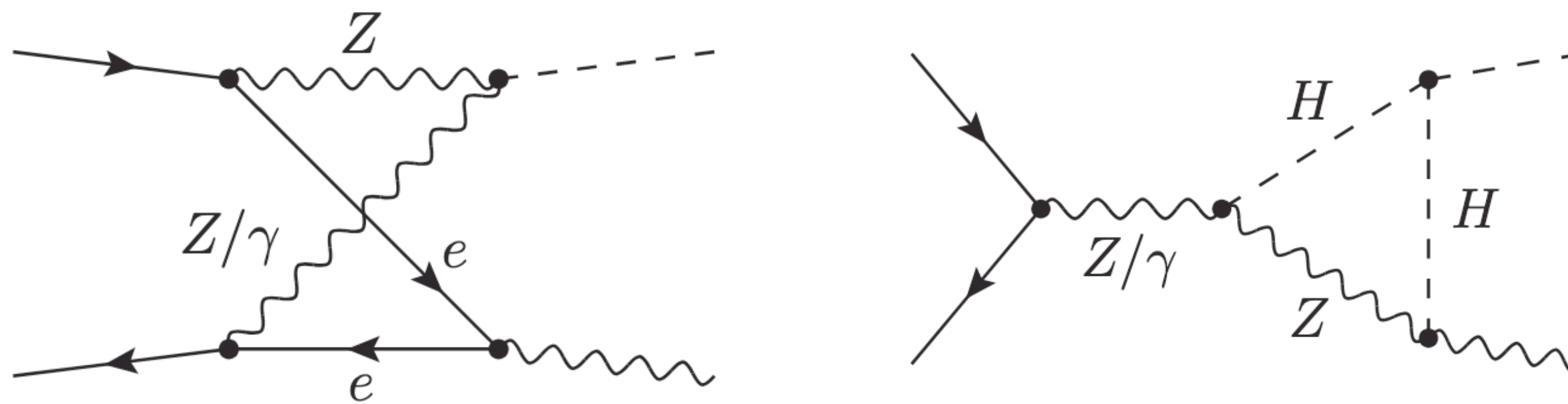
$e^+e^- \rightarrow ZH$ in the SMEFT

- NLO SMEFT corrections to $e^+e^- \rightarrow Zh$ known
- Depends on 10 coeffs at LO, ~ 70 at NLO

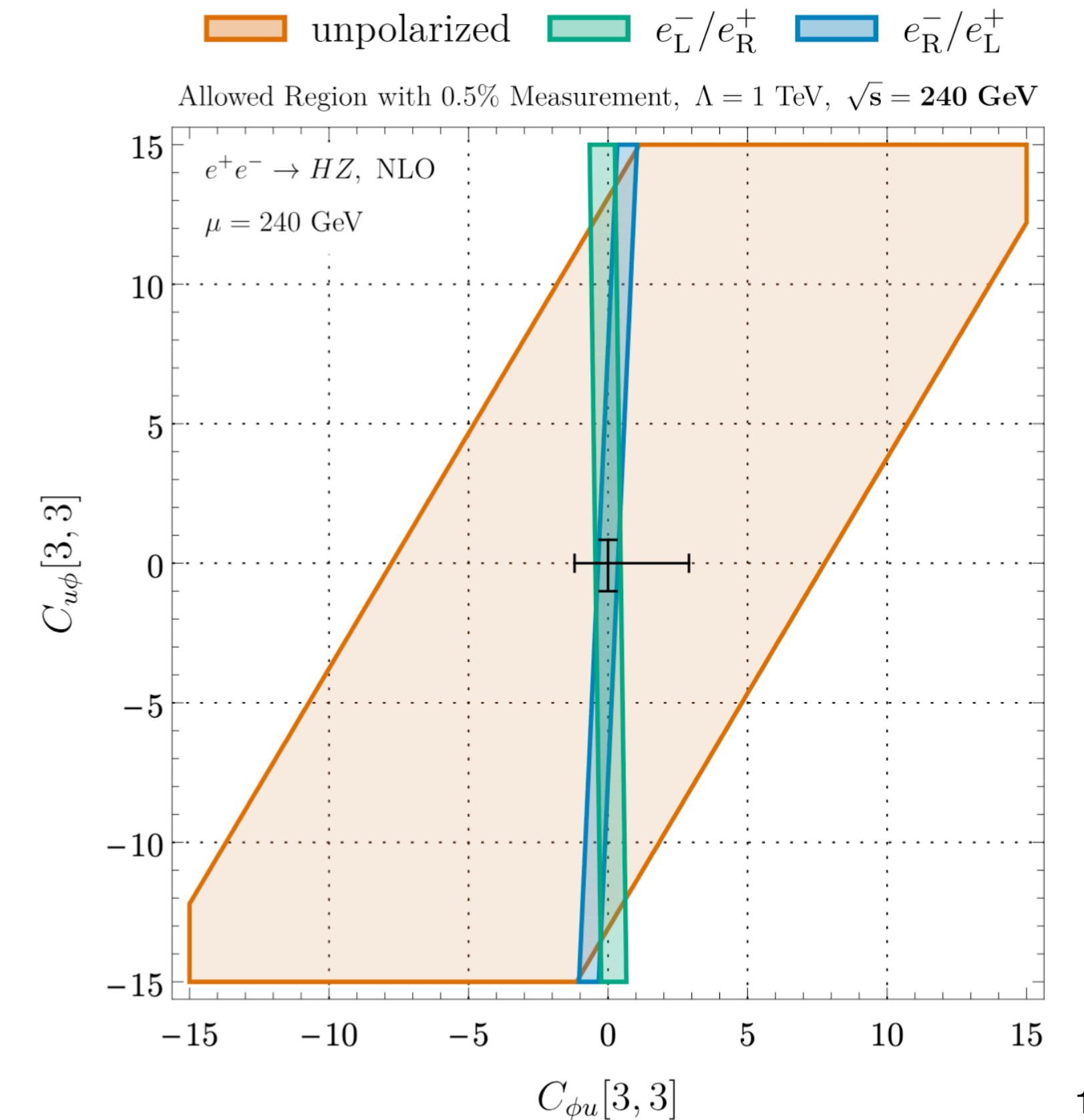
[Asteriadis, Dawson, Giardino, Szafron PRL 133 \(2024\) 23, 231801](#)

[Asteriadis, Dawson, Giardino, Szafron JHEP 02 \(2025\) 162](#)

Numerical results on [GitLab](#)



- Needs to be combined with Z and H decays for the full fit!



Higgs decays in the SMEFT

- $H \rightarrow b\bar{b}$ [Gauld, Pecjak, Scott, PRD 94 \(2016\) 7, 074045](#) [Cullen, Pecjak, Scott, JHEP 08 \(2019\) 173](#) [Cullen, Pecjak, JHEP 11 \(2020\) 079](#)
- $H \rightarrow \tau^+\tau^-, \mu^+\mu^-, c\bar{c}$ [Gauld, Pecjak, Scott, JHEP 05 \(2016\) 080](#) [Cullen, Pecjak, JHEP 11 \(2020\) 079](#)
- $H \rightarrow gg$ [Deutschmann, Duhr, Maltoni, Vryonidou, JHEP 12 \(2017\) 063](#) [Corbett, Martin, Trott JHEP 12 \(2021\) 147](#) [Martin, Trott JHEP 01 \(2024\) 170](#)
- $H \rightarrow \gamma\gamma$ [Hartmann, Trott, PRL 115 \(2015\) 19, 191801](#) [Dawson, Giardino, PRD 98 \(2018\) 9, 095005](#)
[Hartmann, Trott, JHEP 07 \(2015\) 151](#) [Dedes, Paraskevas, Rosiek, Suxho, Trifyllis JHEP 08 \(2018\) 103](#)
- $H \rightarrow Z\gamma$ [Dawson, Giardino, PRD 97 \(2018\) 9, 093003](#) [Dedes, Suxho, Trifyllis JHEP 06 \(2019\) 115](#)
- $H \rightarrow ggZ$ [Rossia, Thomas, Vryonidou JHEP 11 \(2023\) 132](#)
- $H \rightarrow \ell^+\ell^-Z$ [Dawson, Forsslund, Giardino, PRD 111 \(2025\) 1, 015016](#)
- $H \rightarrow q\bar{q}Z$ [Bellafronte, Dawson, Del Pio, Forsslund, Giardino, PRL 136 \(2026\) 5, 051801](#)
- $H \rightarrow f\bar{f}W^\pm$ [Bellafronte, Dawson, Del Pio, Forsslund, Giardino, \[2601.09599\]](#)

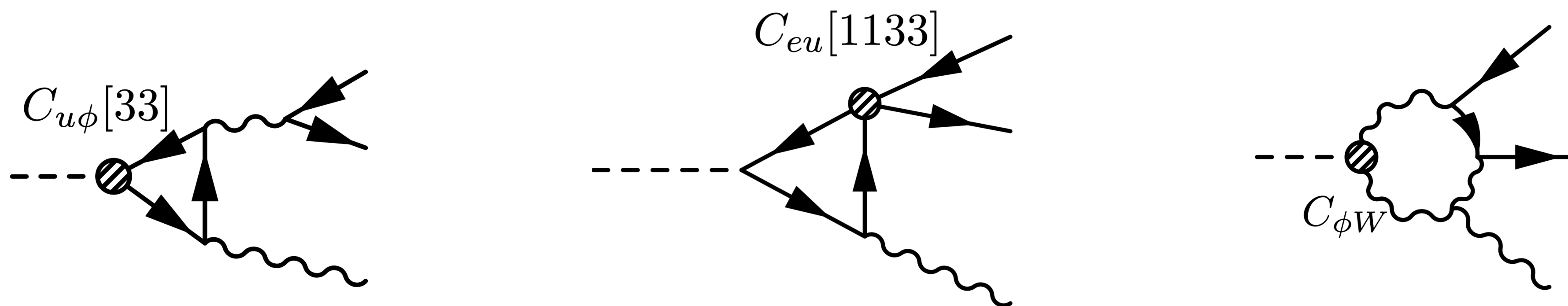
NEWiSH

- Fixed-order Monte Carlo code
- Consistent implementation of all major H partial widths at NLO QCD and EW in the SMEFT
- Exact $H \rightarrow 4f$ at LO, NWA at NLO
- All Higgs decays also now known at NLO*: can combine with $e^+e^- \rightarrow ZH$ and do fully NLO accurate constraints!

[Bellafronte, Dawson, Del Pio, MF, Giardino](#)

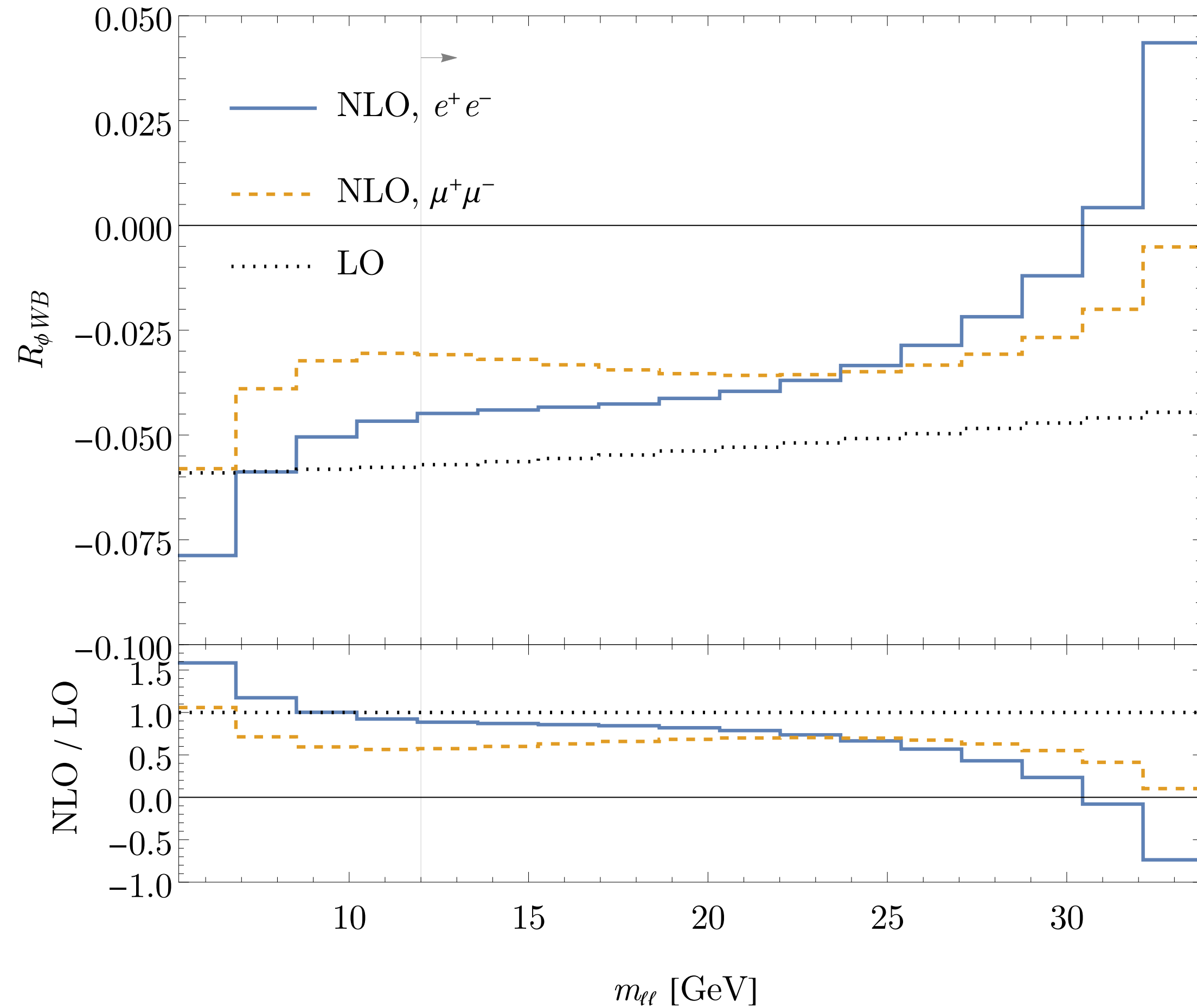
NLO
Electro-Weak
in the
SMEFT for
Higgs widths

<https://gitlab.com/mforslund/newish>
Numerical results also on [GitLab](#)



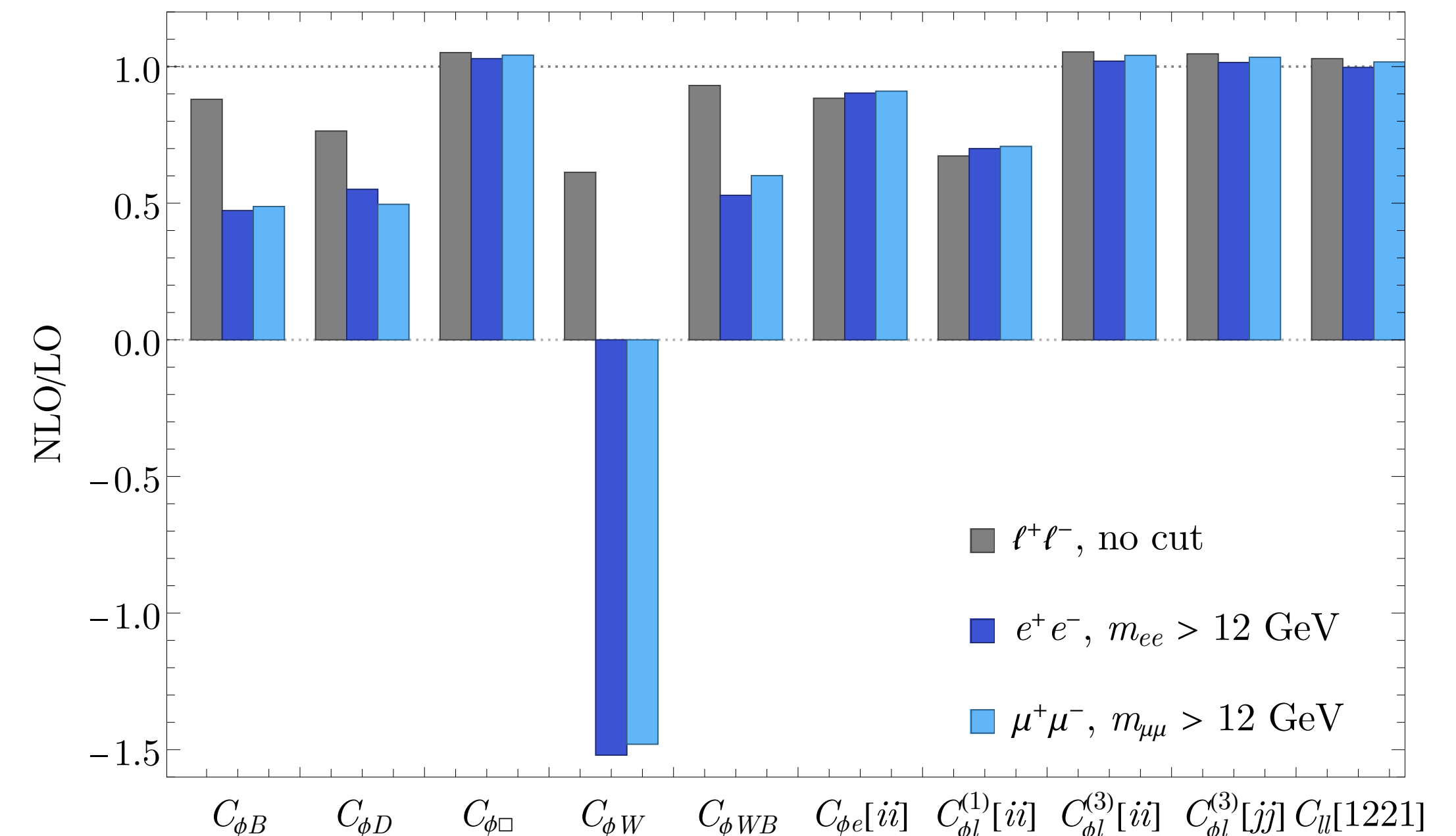
Corrections can be large

$C_{\phi WB}, 1/\Lambda^2, \Lambda = 1 \text{ TeV}$



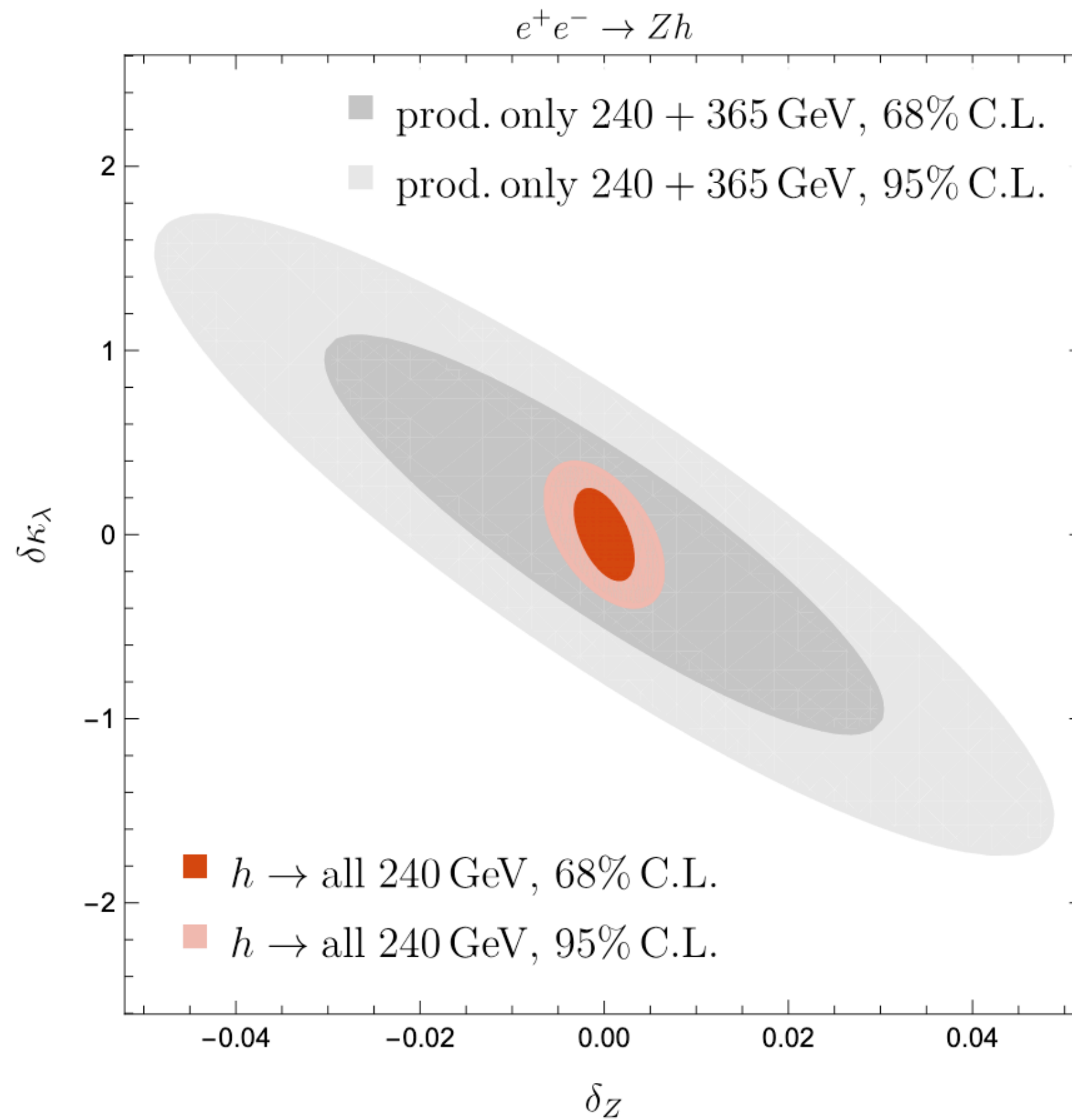
$R_i = \text{EFT/SM}$

- Up to 40% corrections to some LO operators at NLO
- With realistic experimental cuts, corrections become even larger



Higgs self-coupling at FCC-ee

- Equivalently, in terms of κ 's*
- Only linear pieces, consistent with $\mathcal{O}(1/\Lambda^2)$ truncation



Bellafronte, Dawson, Del Pio, MF, Giardino

*Depends on 3 coeffs — we took $C_{\phi\Box} = 0$ here

At 1-loop, operators contribute to many observables

- At FCC-ee, most stages will be precise enough that SMEFT loops matter
- Each process should be computed at NLO accurate for the general fit
- Done:
 - $e^+e^- \rightarrow ZH$ and decays
 - EWPO
- Wishlist:
 - $H \rightarrow 4f$ beyond the NWA
 - $e^+e^- \rightarrow t\bar{t}$ (in progress)
 - $e^+e^- \rightarrow W^+W^-$
 - $e^+e^- \rightarrow (\nu\bar{\nu}, \ell\ell)H$
- At one-loop, operators contribute to all the FCC-ee stages, not just Higgs
- Higgs physics is not just $e^+e^- \rightarrow ZH$

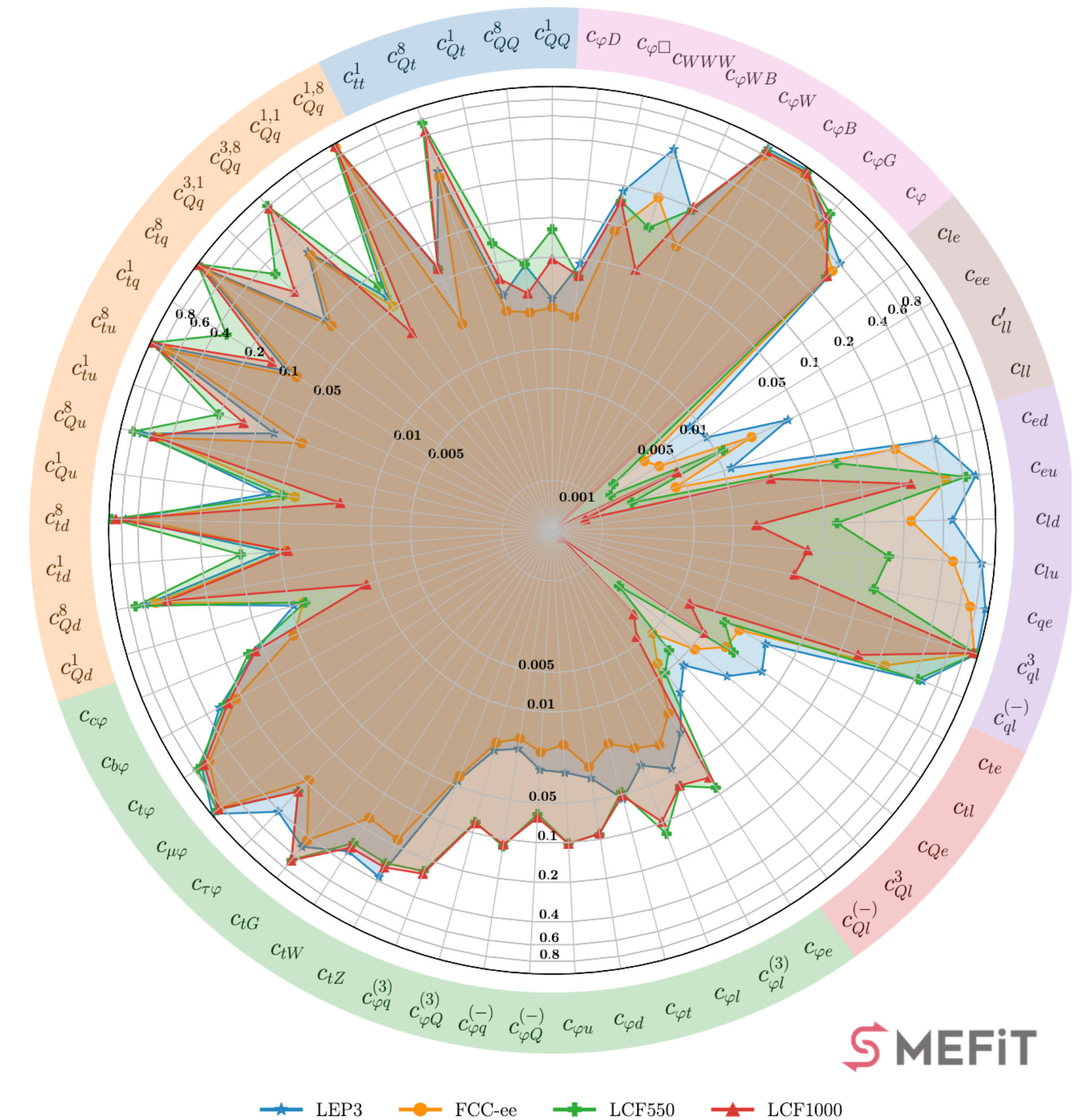
At 1-loop, operators contribute to many observables

- Global fits including NLO Higgs eventually for better picture

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- Global fits including NLO Higgs eventually for better picture
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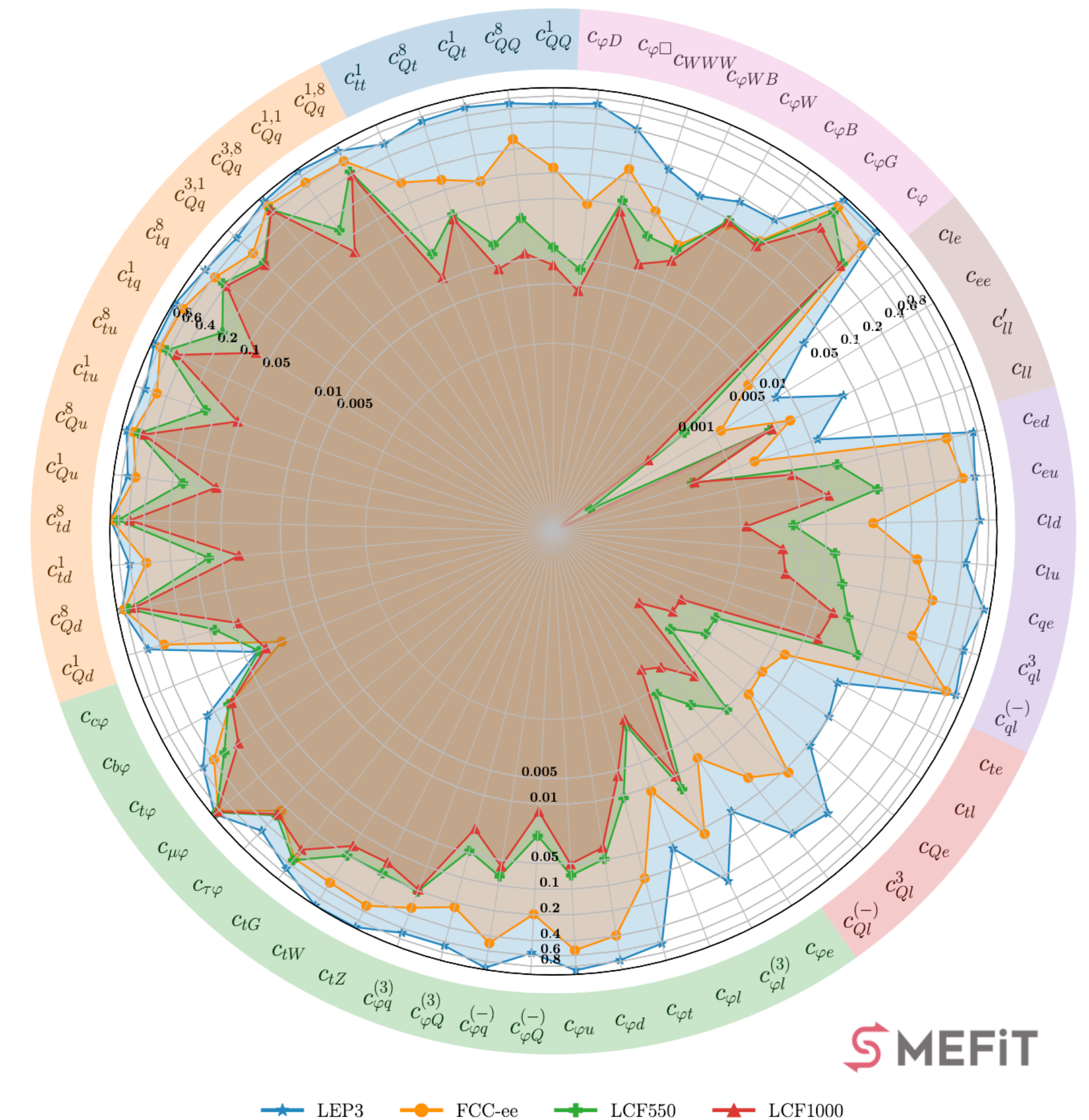
Ratio of Uncertainties to HL-LHC Baseline $\mathcal{O}(\Lambda^{-2})$, Individual



At 1-loop, operators contribute to many observables

- Global fits including NLO Higgs eventually for better picture
- Least conservative: one operator at a time
- Most conservative: fully marginalized
 - Many approximate flat directions
- Any actual UV model will have patterns and lie somewhere between these two fits

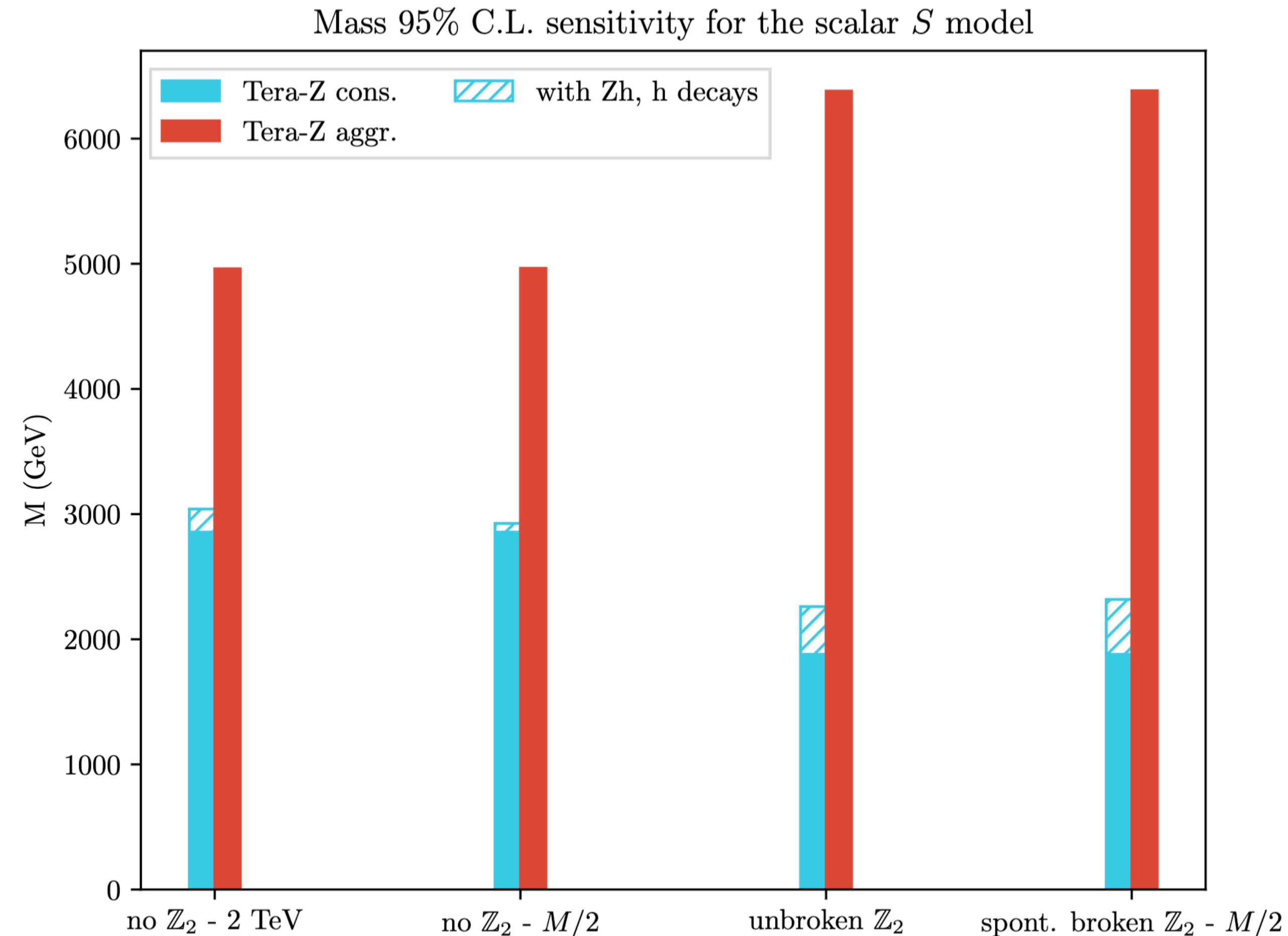
Ratio of Uncertainties to HL-LHC Baseline $\mathcal{O}(\Lambda^{-2})$, Marginalised



Electroweak Precision is also Higgs Physics

- For actual models: loops + RG can make EWPO as important
- Even a scalar singlet can be probed at Tera-Z as well as with Higgstrahlung
- Depends crucially on theory uncertainties at Tera-Z

$$V(\Phi, S) = -\mu_H^2 \Phi^\dagger \Phi + \lambda_H (\Phi^\dagger \Phi)^2 + \frac{m_\xi}{2} \Phi^\dagger \Phi S + \frac{\kappa}{2} \Phi^\dagger \Phi S^2 + t_S S + \frac{M^2}{2} S^2 + \frac{m_\zeta}{3} S^3 + \frac{\lambda_S}{4} S^4.$$



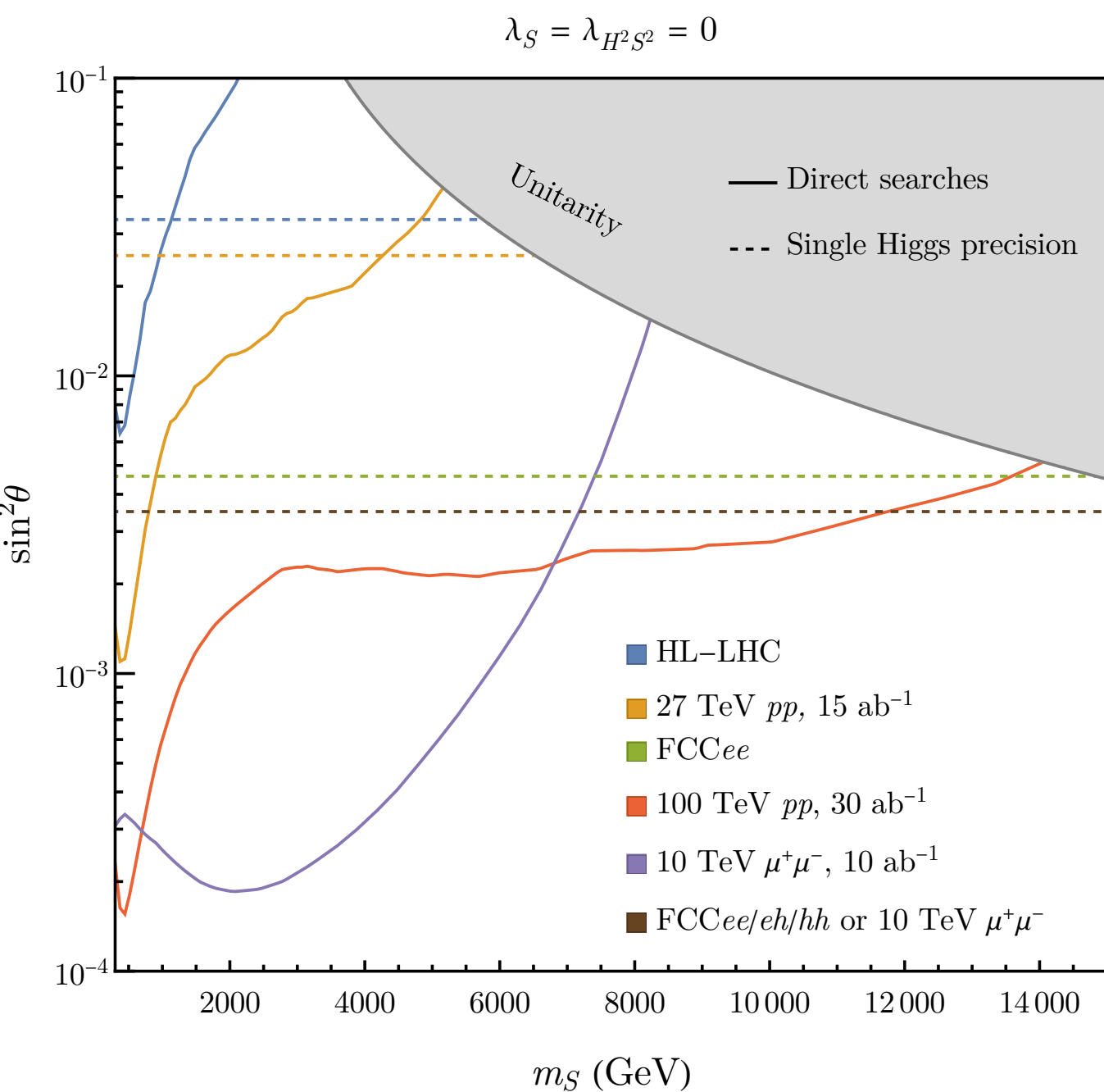
Bellafronte, Dawson, Del Pio, MF, Giardino

*Used 1-loop RGEs, 2-loop available now

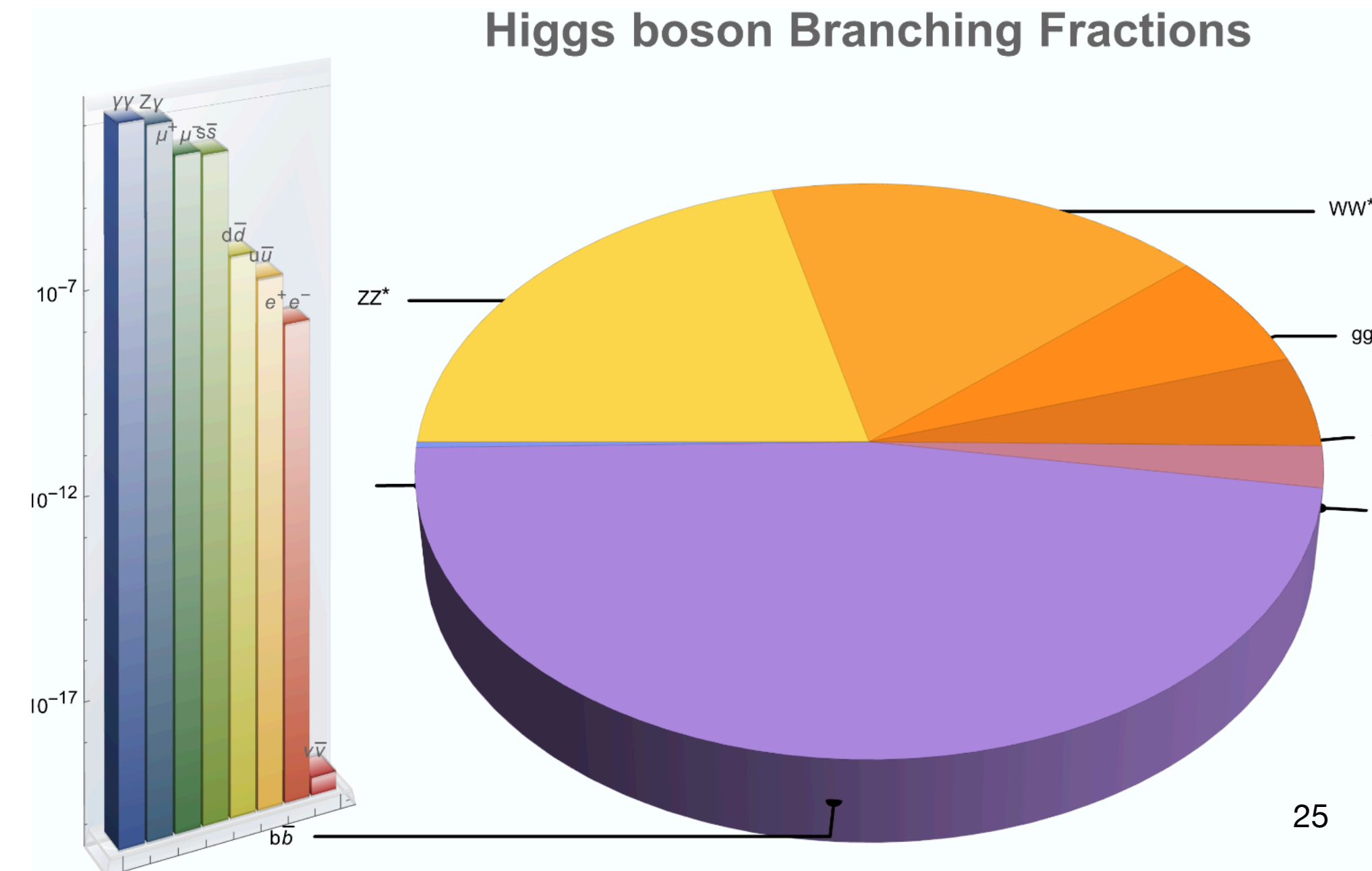
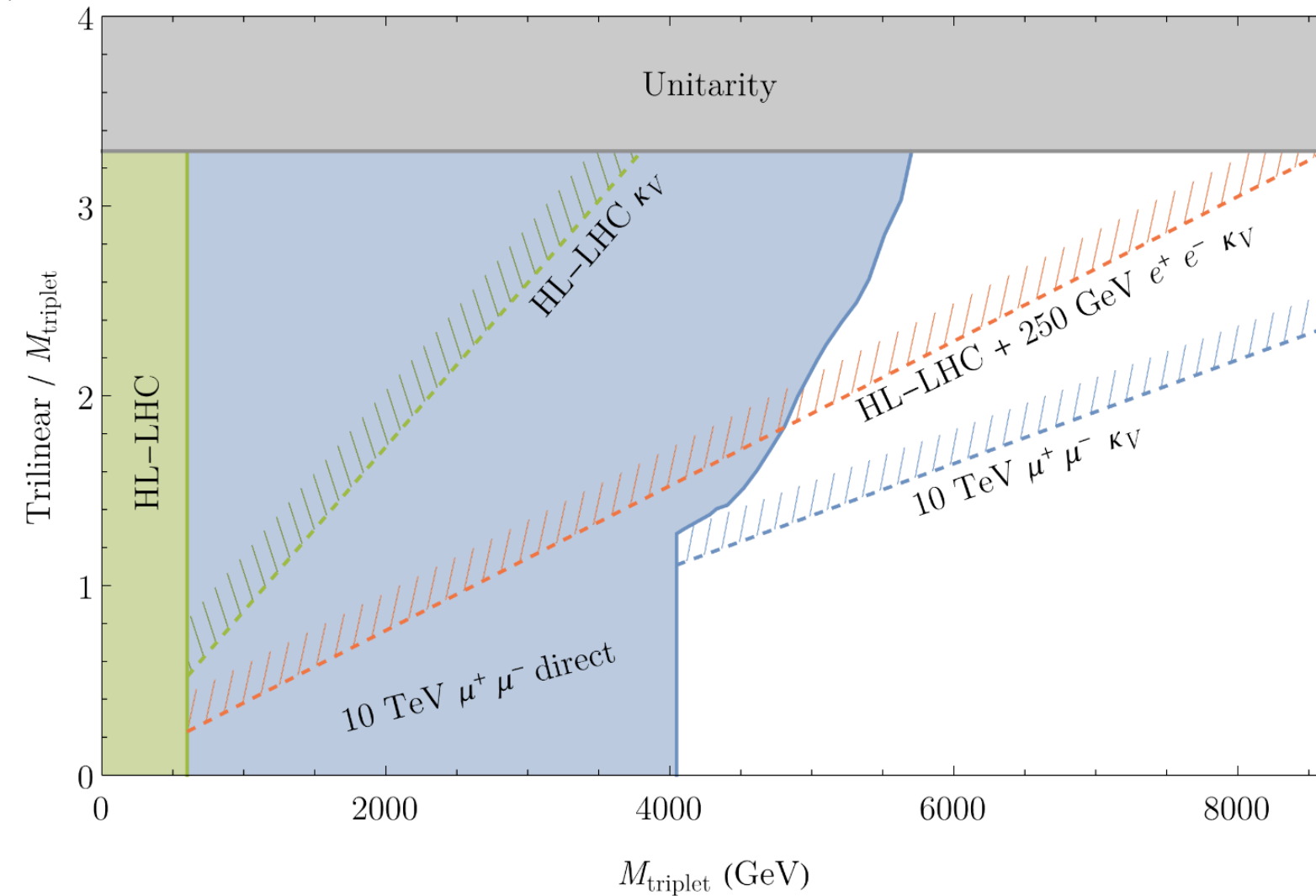
Born, Fuentes-Martín, Thomsen

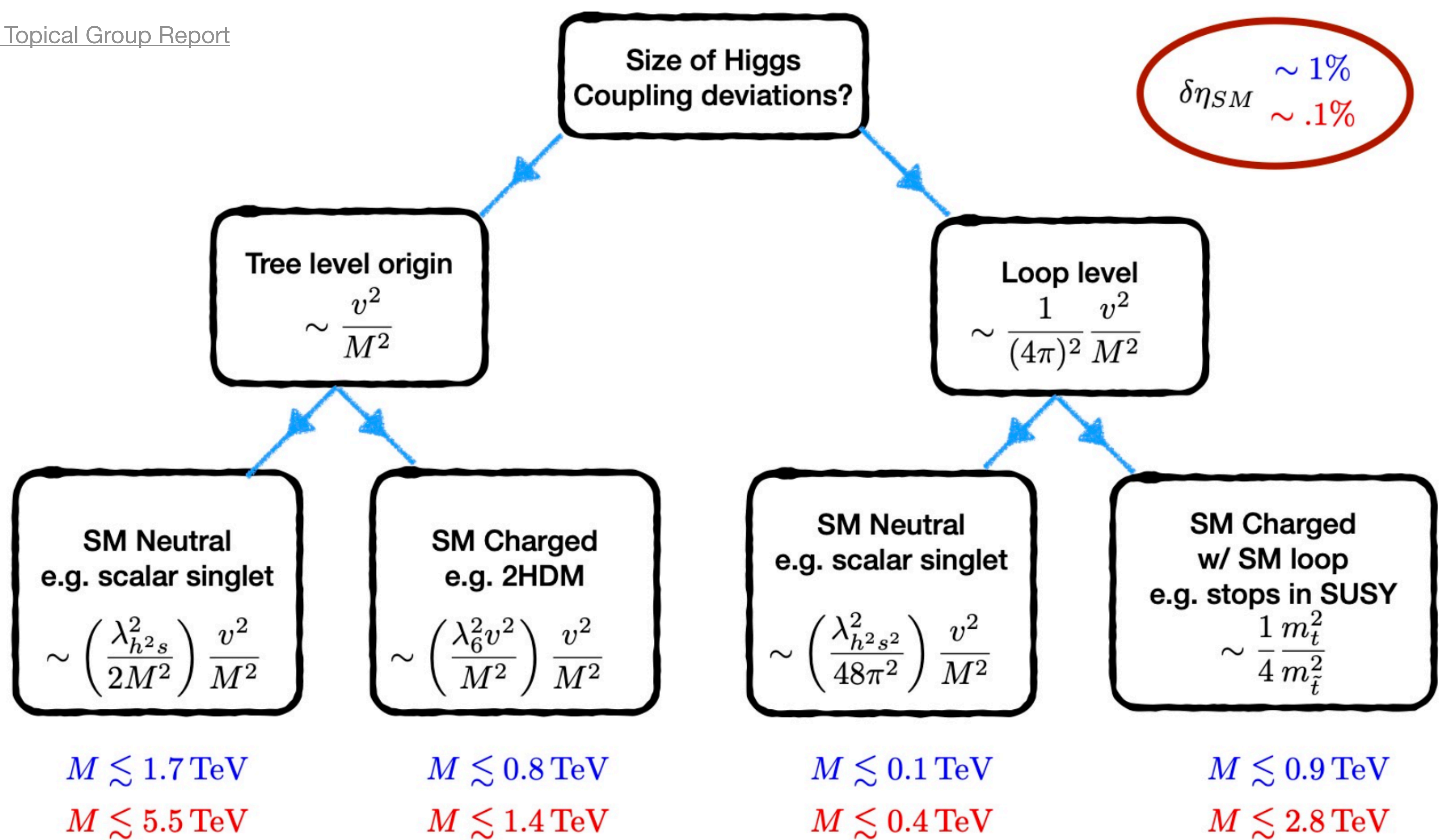
What is the goal?

- Measuring couplings is a good first step, but we want to find new states!
- Many Higgs branching ratios hopelessly out of reach at factories
 - Even if we find a deviation, will be extremely difficult to unambiguously connect to the UV
- We need to produce the BSM particle directly!

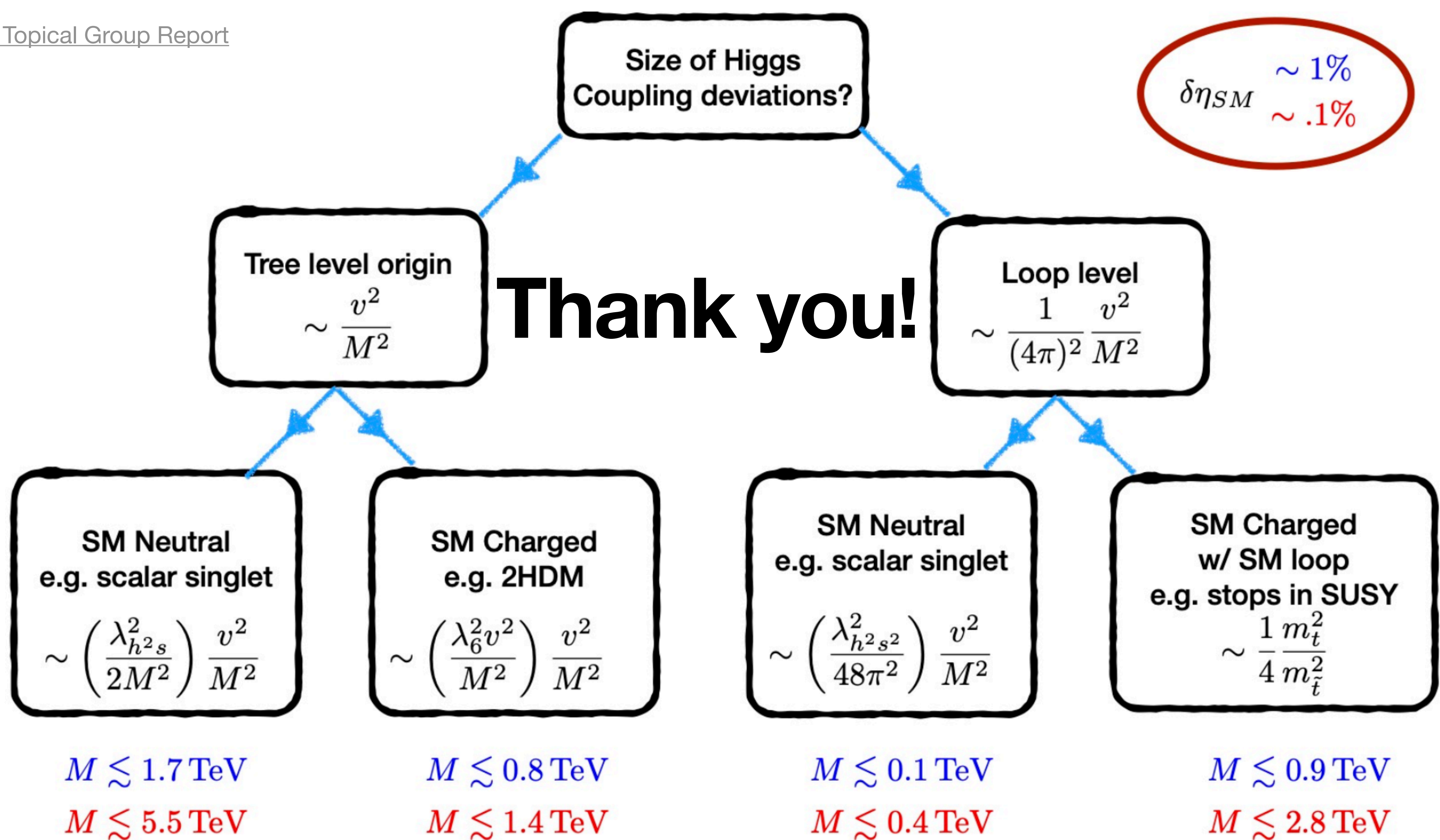


MF, Meade





- Higgs precision reach for UV complete models gets you to $\mathcal{O}(10 \text{ TeV})$
- High energy pp or $\ell^+ \ell^-$ must remain the eventual goal. Precision is just the first step to get there!

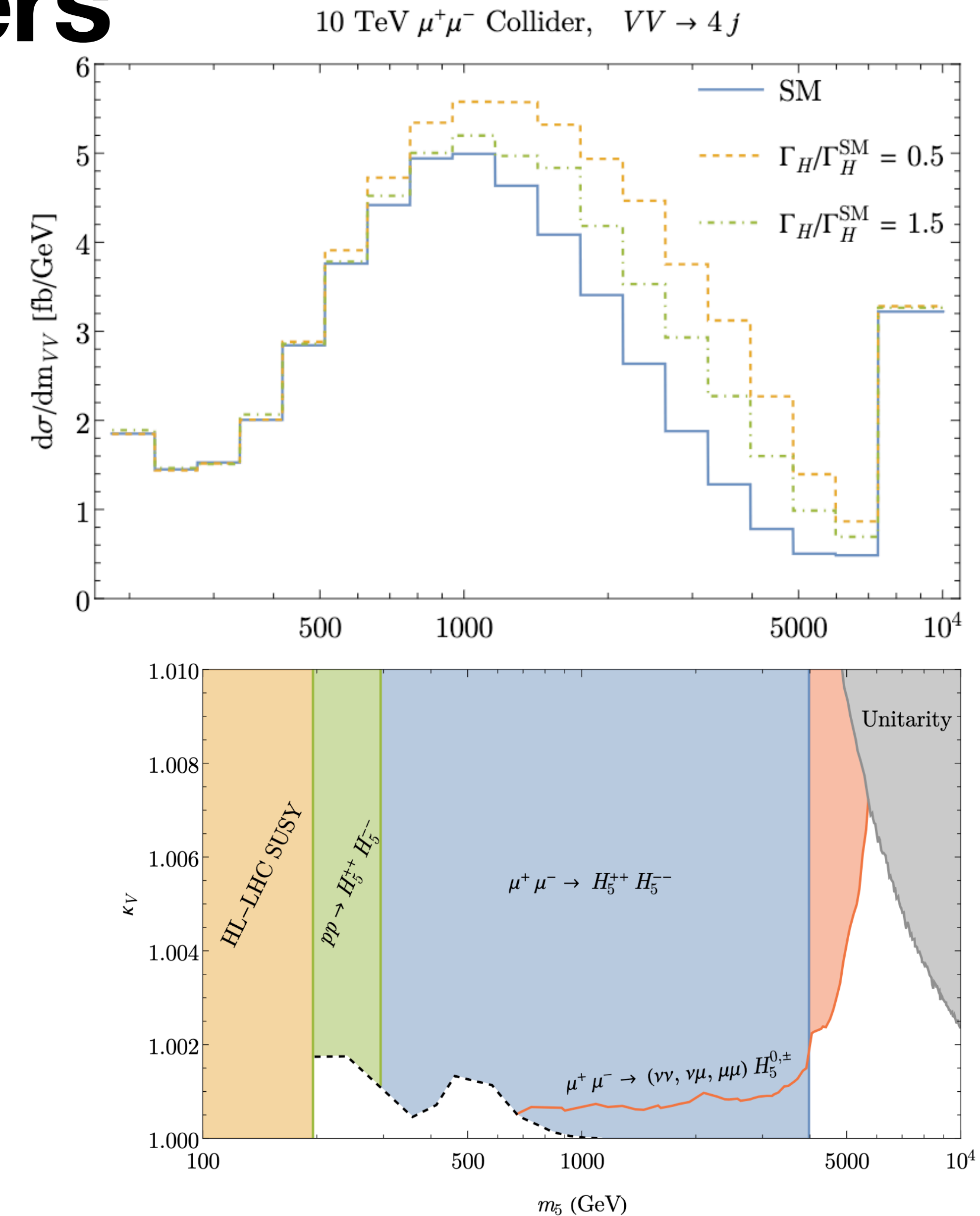


- Higgs precision reach for UV complete models gets you to $\mathcal{O}(10 \text{ TeV})$
- High energy pp or $\ell^+ \ell^-$ must remain the eventual goal. Precision is just the first step to get there!

Backups

Higgs width at muon colliders

- Can constrain the width by taking ratio of on-shell / off-shell VV production
- Model-dependent, not comparable to ZH at FCC-ee
- For any weakly coupled UV completion: direct searches save the day and restore $\mathcal{O}(0.1\%)$ precision
- Alternatively, can constrain width with inclusive ZZ -fusion measurement [Li, Liu, Lyu](#)



Scheme dependence

		C_{HD}	C_{HWB}	C_{He}_{33}	C_{Hu}_{33}	$C_{Hq}_{33}^{(3)}$
v_μ^{eff}	LO	$-0.500^{+0.033}_{-0.033}$	$0.000^{+0.000}_{-0.000}$	$-1.843^{+0.048}_{-0.048}$	$0.000^{+0.052}_{-0.052}$	$0.000^{+0.000}_{-0.000}$
	NLO	$-0.527^{+0.005}_{-0.000}$	$0.004^{+0.000}_{-0.000}$	$-1.905^{+0.004}_{-0.000}$	$0.048^{+0.000}_{-0.013}$	$0.022^{+0.000}_{-0.004}$
v_α^{eff}	LO	$0.000^{+0.000}_{-0.000}$	$2.370^{+0.081}_{-0.081}$	$-1.843^{+0.050}_{-0.050}$	$0.000^{+0.003}_{-0.003}$	$0.000^{+0.005}_{-0.005}$
	NLO	$-0.001^{+0.000}_{-0.000}$	$2.439^{+0.000}_{-0.006}$	$-1.903^{+0.004}_{-0.000}$	$0.005^{+0.000}_{-0.001}$	$0.002^{+0.000}_{-0.000}$
α_μ	LO	$-0.169^{+0.011}_{-0.011}$	$0.355^{+0.012}_{-0.012}$	$-1.764^{+0.046}_{-0.046}$	$0.000^{+0.018}_{-0.018}$	$0.000^{+0.001}_{-0.001}$
	NLO	$-0.289^{+0.009}_{-0.007}$	$0.258^{+0.003}_{-0.004}$	$-1.897^{+0.006}_{-0.002}$	$0.018^{+0.011}_{-0.016}$	$0.006^{+0.000}_{-0.002}$
α	LO	$1.573^{+0.108}_{-0.108}$	$4.088^{+0.143}_{-0.143}$	$-1.764^{+0.050}_{-0.050}$	$0.000^{+0.162}_{-0.162}$	$0.000^{+0.008}_{-0.008}$
	NLO	$1.408^{+0.002}_{-0.019}$	$3.869^{+0.002}_{-0.013}$	$-1.898^{+0.006}_{-0.002}$	$-0.142^{+0.030}_{-0.000}$	$-0.073^{+0.014}_{-0.000}$
LEP	LO	$-0.600^{+0.040}_{-0.040}$	$-0.474^{+0.016}_{-0.016}$	$-1.837^{+0.048}_{-0.048}$	$0.000^{+0.062}_{-0.062}$	$0.000^{+0.001}_{-0.001}$
	NLO	$-0.631^{+0.005}_{-0.000}$	$-0.475^{+0.001}_{-0.000}$	$-1.899^{+0.004}_{-0.000}$	$0.057^{+0.000}_{-0.015}$	$0.025^{+0.000}_{-0.005}$

SM	$C_{H\Box}$	C_{HD}	C_{dH}_{33}	C_{HWB}	$C_{Hl}_{jj}^{(3)}$	C_{ll}_{1221}
.3%	20.3%	20.3%	20.3%	20.3%	-	-
2 %	2.1%	-11.0%	4.2%	-6.7%	-	-
.1%	22.4%	9.3%	24.5%	13.6%	-	-
.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
8 %	2.1%	2.0%	1.9%	-	0.9%	-0.8%
.5%	22.4%	22.3%	22.2%	-	21.2%	19.5%
.3%	20.3%	20.3%	20.3%	-	20.3%	20.3%
7 %	2.1%	1.6%	1.9%	-	0.7%	-0.9%
.5%	22.3%	21.9%	22.2%	-	21.0%	19.3%

Table 6: Selected SMEFT contributions to the $Z \rightarrow \tau\tau$ decay rate including scale variation in the five schemes.

Biekötter, Pecjak, Smith

Biekötter, Pecjak, Scott, Smith